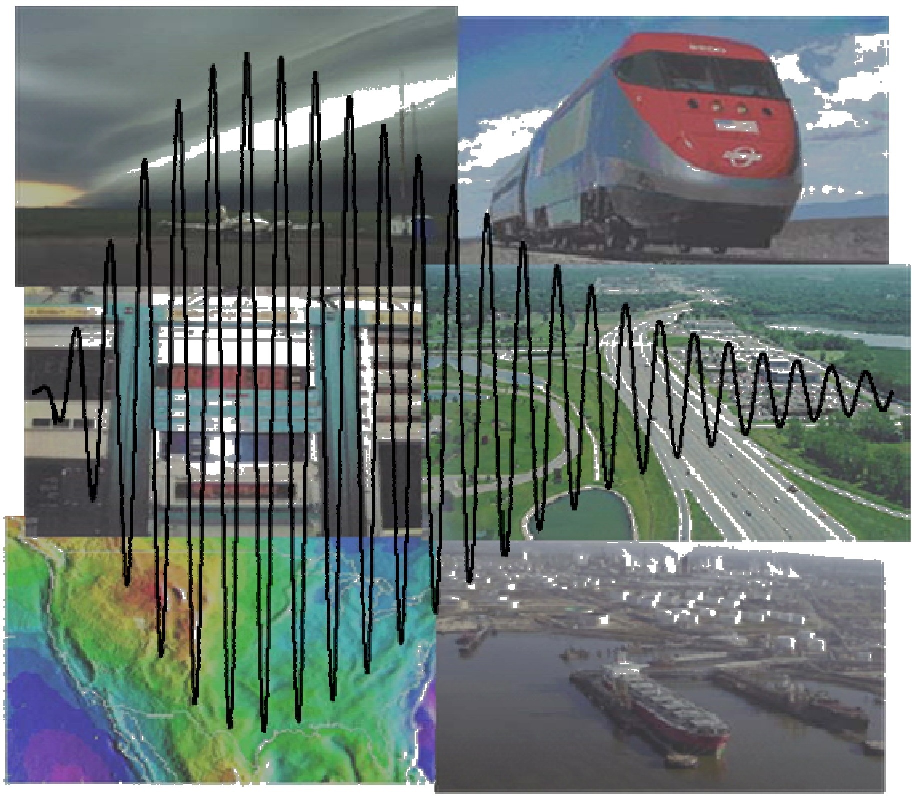
Loran's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications



Prepared for the
FEDERAL AVIATION ADMINISTRATION
VICE PRESIDENT FOR TECHNICAL OPERATIONS
NAVIGATION SERVICES DIRECTORATE

March 2004

PROGRAM MANAGER'S NOTE

The evaluation to determine whether a Loran system can satisfy the current non-precision approach (NPA), harbor entrance approach (HEA), and timing and frequency requirements was successful. The evaluation was completed under Federal Aviation Administration sponsorship; however, the team's structure and purpose was multi-modal and multi-organizational. The Loran evaluation team's purpose was to determine, from a technical perspective, whether Loran could be used as a safe, accurate, reliable, and cost-effective alternative position, navigation, and time system during an outage of the Global Positioning System (GPS) or its augmentations (e.g., Differential GPS, Wide Area Augmentation System). Thus, the evaluation was done not for the benefit of Loran users but for the benefit of current and future GPS users, so that they might retain the benefits they derive from their use of GPS. *The evaluation shows that a modernized Loran-C system could satisfy the current NPA, HEA, and timing/frequency requirements in the conterminous United States and could be used to mitigate the operational effects of a disruption in GPS services, thereby allowing the GPS users to retain the benefits they derive from their use of GPS.*

This report describes modifications to the existing Loran-C system that could make Loran capable of meeting NPA for aviation, HEA for maritime, and time/frequency user needs. If the decision is made to retain Loran as one of the federally provided radionavigation systems, the extent to which these modifications are accepted and implemented will define the actual characteristics of the resulting enhanced Loran (eLoran) system.

The efforts documented herein are a compilation of contributions from many people who are or who have been involved with the Loran system. Their accomplishments in supporting this evaluation attest to their dedication to the improved safety of all radionavigation users under the best and worst of conditions. Current and future users of the Loran system, whether on land, in the air, or at sea or involved in other critical applications, should understand that their safety was the foremost consideration of this evaluation.

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EXECUTIVE OVERVIEW

This report documents the Federal Aviation Administration's (FAA) **LO**ng **RA**nge **N**avigation[1] (Loran) evaluation program's results as requested by the Department of Transportation's (DOT) Undersecretary for Policy in his role as the Chair of the DOT Positioning and Navigation Committee. An evaluation team comprising government agency, industry, and academic representatives conducted this evaluation. The team's focus was to determine whether Loran could meet current aviation and maritime radionavigation, as well as and time/frequency applications requirements, thus providing a viable, cost-effective alternative to the Global Positioning System (GPS) in the event of a GPS outage.[2] The position, navigation, and time (PNT) applications evaluated include aviation navigation through non-precision approach (NPA) operations, maritime navigation through harbor entrance and approach (HEA) operations, and time and frequency distribution through the Stratum 1 level. *The evaluation results conclude that a modernized Loran system can satisfy the current NPA, HEA, and timing/frequency requirements in the conterminous United States.* The following paragraph provides a brief description of this modernized system.

> The modernized Loran system continues to be a low-frequency, terrestrial navigation system operating in the 90- to 110-kHz frequency band and synchronized to coordinated universal time. However, this modernized Loran system has a recapitalized infrastructure and a new communication modulation method that enables operations that satisfy the accuracy, availability, integrity, and continuity performance requirements for non-precision approaches and harbor entrance and approaches, as well as the requirements of non-navigation time and frequency applications. Required changes to the current system include modern solid-state transmitters, a new time and frequency equipment suite, modified monitor and control equipment, and revised operational procedures that new receiver technology can exploit.

Reason for Evaluation

The U.S. Coast Guard (USCG) has provided the Loran service for over 40 years. Loran has been used for navigation in various transportation modes and for precise timing and frequency applications. In the 1980s, in response to user and industry requests, the USCG and FAA jointly conducted a project to expand the area of Loran-C coverage and to close the so-called "mid-continent coverage gap." This project was completed in late 1990. The coverage area as defined, circa 1990, is shown in Figure EO-1. Although the desired coverage was achieved, other required aspects of the system's performance were not met.[3] Consequently, the system failed to gain full FAA and user acceptance, and

[1] **LO**ng **RA**nge **N**avigation; H.O. Pub 220 Navigation Dictionary, 2nd edition 1969.

[2] This evaluation examines GPS applications and how modernized Loran can mitigate the impact of a GPS outage (e.g., satellites are not available for whatever reason—failure, blockage, jammed). The evaluation did not examine Loran-C applications; the evaluation was done for the benefit of the GPS users so that they may retain the benefits derived from their use of GPS.

[3] This was largely due to transmitter and user equipment performance limitations. These limitations were addressed by this evaluation. The analysis conducted and data collected during this evaluation indicate that these limitations have been resolved by the technology now available for the new transmitting, monitoring and control, and user equipment.

attempts to obtain FAA certification of NPA-capable receivers were unsuccessful. Then, in 1994, the Federal Radionavigation Plan (FRP) stated that Loran-C would be terminated in 2000. In the late 1990s, this situation changed due to the growing concern about the vulnerability of GPS and how the loss of GPS might affect the U.S. critical infrastructure. This is the topic of the John A. Volpe National Transportation System Center (Volpe) report, "The Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," of August 20, 2001, and the FAA ASD-1 report, "Navigation and Landing Transition Strategy," of August 2002. This concern refocused attention on Loran-C and its use as a possible redundant system for position, navigation, and timing/frequency services.[4] Due to the renewed interest, this

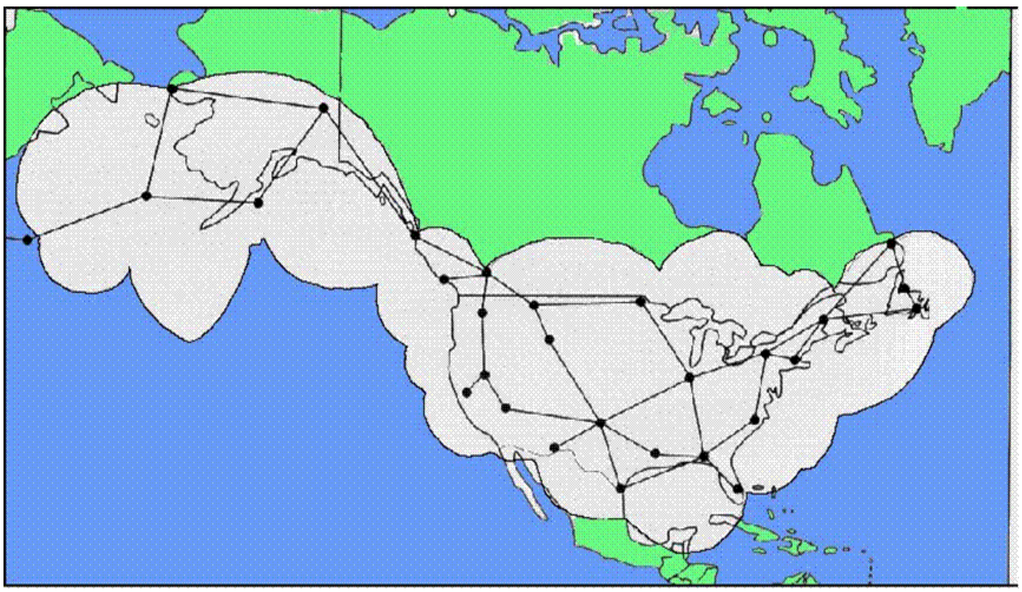


Figure EO-1. Loran-C Coverage as Shown in the Federal Radionavigation Plan (Based on Past Requirements and an Individual Loran-C Chain Operation)

evaluation of Loran has been supported, beginning in 1997, by congressionally mandated funding that directed the FAA "…to further develop the Loran-C system."[5] Through the use of this congressional funding, extensive work has been accomplished to overcome both transmitter and user equipment performance limitations and to conduct analyses that determine whether the modernized Loran system can meet the NPA, HEA, and time/frequency performance requirements.

Evaluation Team's Work Plan

The multi-year effort began with the understanding that aviation and maritime requirements would remain as stated in the FRP, that is, a 0.25-nm 2-drms system with availability and reliability of 99.7 percent. However, the requirements and the methods by which navigation performance requirements are derived and stated were actually

[4] One of Loran-C's strengths is that it provides a horizontal area navigation (RNAV) capability.

[5] This was also part of the FY 96 USCG Authorization Act, in which Congress directed the Secretary of Transportation to develop a plan for the continuation of Loran into the next century.

evolving. These redefinitions were largely prompted by the unprecedented capabilities of GPS and the fact that the Department of Defense's development of GPS did not include transportation system safety as a significant design factor. The current requirements for an application—not those provided in the FRP—were used for this evaluation.

Since the beginning of the evaluation, numerous papers and presentations that document and support the work and conclusions of this report have been provided to both national and international audiences. This documentation includes a report prepared by the evaluation team for DOT on the interim status of the evaluation, titled "An Analysis of Loran-C Performance, Its Suitability for Aviation Use and Potential System Enhancements." Additionally, the team used the extensive existing technical body of knowledge on Loran-C to support the evaluation's conclusions.

This report presents the work conducted, the conclusions reached regarding the structure and capabilities of a modernized Loran system, and the recommendations for further work.

Conclusion

The evaluation shows that the modernized Loran system can satisfy the current NPA, HEA, and timing/frequency requirements in the conterminous United States and could be used to mitigate the operational effects of a disruption in GPS services, thereby allowing the users to retain the benefits they derive from their use of GPS. This conclusion is based on an analysis of the applications' performance requirements; expected modification of radionavigation policies, operating procedures, transmitter, monitor and control processes, and user equipment specifications; completion of the identified Loran-C infrastructure changes; and results from numerous field tests. Collectively, these create the architecture for the modernized Loran system.

Based on the technical evaluation and the modal user application's requirement, the expected modernized Loran coverage, as determined from the evaluation team's analysis, is depicted in Figure EO-2 and Figure EO-3. These figures illustrate the expected coverage using aviation Required Navigation Performance (RNP) 0.3 availability requirements and HEA accuracy requirements.[6] Due to the methods and assumptions used by the evaluation team, these are conservative estimates of the coverage. It should be noted that the analysis discussed herein focused primarily on the conterminous United States. Alaska presents a very different radio propagation environment, and different measures may be required to mitigate early skywave effects in that state. The technical team has studied this issue, but schedule has prevented a complete analysis. However, the methodology described herein can readily be applied in Alaska.[7]

To complement the evaluation team's technical perspective, an assessment of the benefits and costs associated with the modernized Loran system was conducted by the Volpe

[6] The changes required for the aviation and marine applications also allow the time and frequency application requirements to be met.

[7] Loran-C coverage in Alaska is briefly discussed in Appendix C and papers listed in Appendix D.

Center.[8] Although done concurrently with the technical evaluation, it was an independent effort, so it is not discussed in this report.

This report describes modifications to the existing Loran-C system that could make Loran capable of meeting NPA for aviation, HEA for maritime, and time/frequency user needs. If the decision is made to retain Loran as one of the federally provided radionavigation systems, the extent to which these modifications are accepted and implemented will define the actual characteristics of the resulting enhanced Loran (eLoran) system.

Finally, the legacy users of Loran-C (i.e., those using previously manufactured Loran-C receiving equipment) are only minimally affected by the changes proposed for the modernized Loran system. However, these legacy receivers will not be able to take full advantage of the accuracy, availability, integrity, continuity, timing, and frequency improvements of the modernized system.

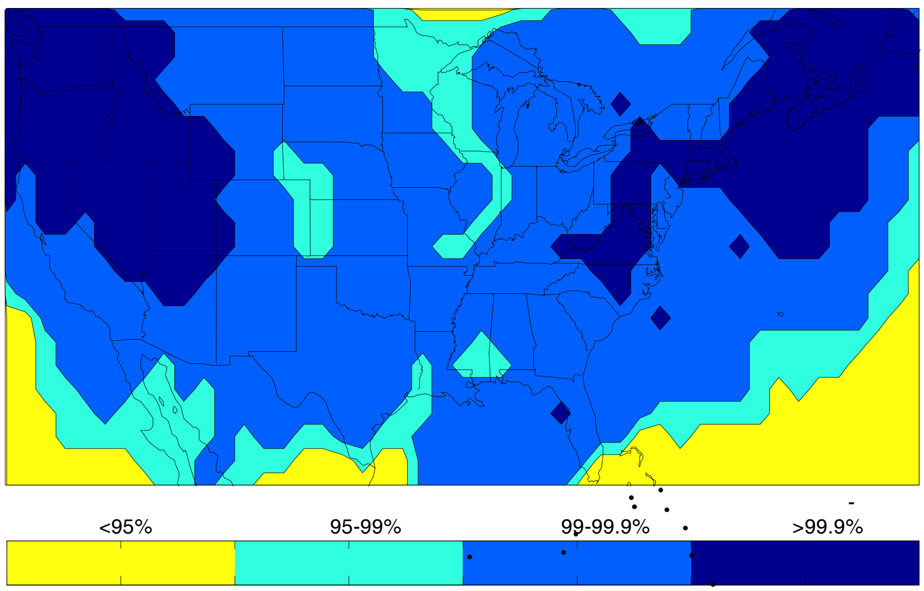


Figure EO-2. Expected RNP 0.3 Modernized Loran Coverage (Availability Contours in Percent) in the Conterminous United States with Existing Infrastructure (Which Includes the Canadians Stations)

[8] "Benefit/Cost Assessment for the Use of Loran-C to Mitigate GPS Vulnerabilities for Position, Navigation, and Timing Services," by the John A. Volpe National Transportation System Center, March 2004.

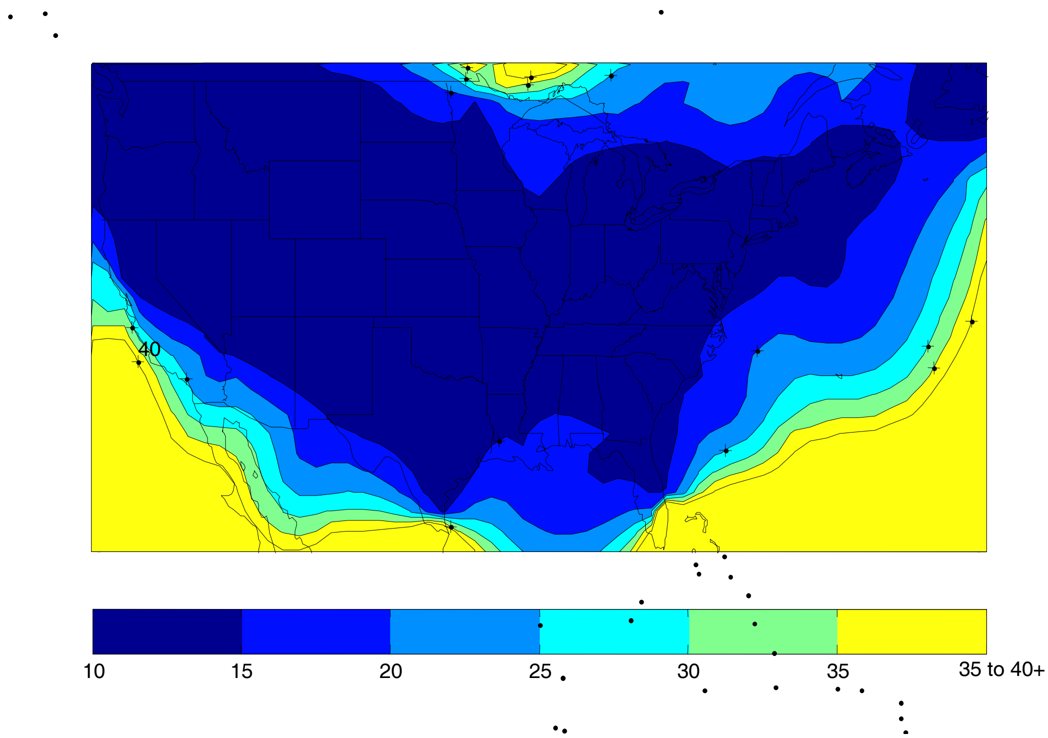


Figure EO-3. Expected HEA Modernized Loran Coverage (Accuracy Contours in Meters at the 95 Percent Noise Level) in the Conterminous United States with the Existing Infrastructure (Which Includes the Canadians Stations)

Recommendation for Follow-on Actions

If the decision is made to continue Loran as a federally provided radionavigation system, the evaluation team recommends that actions be taken by both government and private entities to ensure that the system can reach and sustain its full potential as quickly as possible and into the foreseeable future. If accepted, these recommendations would—

- Determine the actual coverage where the operational requirements are satisfied. (e.g., high-atmospheric noise and Alaska).
- Increase availability.
- Provide the capability for additional applications.
- Ensure a diverse and competitive supply of multi-functional user equipment in the near term and throughout the life of the system.
- Promote the further understanding, development, and adoption of the system.

The team's major recommendations are summarized below. Additional, more detailed, recommendations are provided in the body of this report.

- Complete all remaining facets of the work required to create the modernized Loran-C system including—

- Implement time of transmission control.
- Complete the installation of the solid-state transmitters (SSX).
- Complete the development and deployment of the new Loran modulation method.
- Rewrite the Loran-C Signal Specification.
- Rewrite the Loran-C Operational Doctrine.
- Complete the Harbor and Airport Surveys.
- Develop the receiver specifications for NPA, HEA, and other applications, as required.

- Definitively announce the Federal Government's policy to continue, in the long term, the modernized Loran system as part of the critical national infrastructure for position, navigation, and timing/frequency applications.[9] This will encourage the development and use of the new Loran technologies (improved receivers, antennas, algorithms, etc.).
- Revise inter-agency and international agreements (e.g., Canadian) to address any changes required for the modernized Loran system.
- Develop a multi-agency strategic operation, maintenance, and support plan for the modernized Loran system.
- Identify areas of direct savings or cost avoidance that result from the modernization effort (e.g., installation of SSXs and station moves) that could be reinvested into the modernization effort.
- Identify and support research and development efforts that would be consistent with the modernized Loran capabilities and identify additional critical applications where safety, security, and economic concerns must be met in the event of a GPS outage. For these applications, determine whether the addition of modernized Loran would be practical and beneficial (e.g., how robustness and accuracy of the modernized Loran system's clock can further support the critical timing/frequency infrastructure).
- Further investigate noise and propagation effect to allow for less conservative estimates that better define the system capabilities and improve the Loran models. Specifically, the Loran availability results shown herein are based on widely accepted models for atmospheric noise. These models are accurate when performance is averaged over the year, so most of the availability plots herein are based on annual averages. Availability results for the time blocks when

[9] The evaluation team realizes that "long term" is vague. The team also realizes that if the decision is made to modernize and continue Loran that technical aspects of the conclusion will not be valid unless there is industry and user acceptance. This can be gained only if they are assured that there is sufficient time for benefits to be accrued from the use of modernized Loran. The actual date is beyond the scope of this evaluation and would be predicated on many factors, including information provided in the Volpe benefit/cost assessment, user acceptance, GPS, and Loran strategic plans.

atmospheric noise is strongest show significantly less availability. However, these models are known to be very conservative when predicting the extreme levels of noise power.

- Investigate other methods that analyze and determine a PNT application's performance requirements (e.g., target levels of safety).
- Periodically update benefit/cost assessment data and expand its scope to include business cases for each GPS redundant, back-up, and contingency system, as well as each option for PNT [10]

[10] The marketplace ultimately decides where Loran-C will be used. However, adding Loran-C to approved uses or as a part of an approved application or process may enhance its usefulness and, hence, its value to the marketplace (e.g., VNAV with a barometric altimeter; see Appendix C).

1. INTRODUCTION

Congress designated the Federal Aviation Administration (FAA) as the sponsor of a multi-agency, multi-industry, and academic team "to evaluate" and "to continue development of" the Loran-C system [1], [2]. The team's focus was to determine whether a modernized Loran could meet current radionavigation and timing requirements, thus providing a viable alternative to the Global Positioning System (GPS) in the event of a GPS outage [3]. This report provides a synopsis of the team's methodology for determining and comparing today's Loran-C capabilities with those of the modernized Loran system.[11] The evaluation and the ongoing modernization effort provide support for deciding how Loran could be part of the mix of 21st century radionavigation services provided by the U.S. Government [4], [5], [6], [7], [8]. The need for this formal technical evaluation was identified in March 2002 [9]. To meet the constraints of the federal budget and planning cycle and to allow sufficient time for analysis, completion of the effort was scheduled for the end of March 2004.

This report describes modifications to the existing Loran-C system that could make Loran capable of meeting NPA for aviation, HEA for maritime, and time/frequency user needs. If the decision is made to retain Loran as one of the federally provided radionavigation systems, the extent to which these modifications are accepted and implemented will define the actual characteristics of the resulting enhanced Loran (eLoran) system.

In addition to this technical effort, an independently conducted benefit/cost assessment (BCA) on Loran-C was recently completed by the Volpe National Transportation Systems Center (Volpe) [10]. Because the BCA report and its analyses were independently conducted, they are not discussed in this report.

1.1 EVALUATION SCOPE

This evaluation's primary purpose was to determine whether Loran-C could meet requirements for accuracy, availability, integrity, and continuity of aviation GPS applications. This evaluation used methods similar to those employed by the FAA's Wide Area Augmentation System (WAAS) Integrity Performance Panel (WIPP) [11]. In fact, this evaluation team, to date, is the only group to apply the process used by WIPP to a non-GPS system. The Loran-C evaluation first focused only on aviation applications but later expanded to address the evolving requirements of maritime applications and time/frequency applications. The team, comprising several navigation experts, systematically examined all aspects of Loran-C by adapting the processes of WIPP to determine whether Loran-C could meet the various requirements.

[11] The modernized Loran system continues to be a low-frequency, terrestrial navigation system operating in the 90–110 kHz frequency band and synchronized to coordinated universal time. However, this modernized Loran system has a recapitalized infrastructure and a new communication modulation method that enables operations that satisfy the accuracy, availability, integrity, and continuity performance requirements for non-precision approaches and harbor entrance and approaches, as well as the requirements of non-navigation time and frequency applications. Required changes to the current system include modern solid-state transmitters, a new time and frequency equipment suite, modified monitor and control equipment, and revised operational procedures that new receiver technology can exploit

Prior to March 2002, the evaluation focused more on the ancillary benefits of Loran-C (e.g., a ground-based communications method for WAAS corrections) rather than the navigation aspect of Loran-C. It was believed the navigation requirements were fixed and would not differ from those stated in the Federal Radionavigation Plan (FRP) [4]. However, navigation definitions and requirements within the FAA were significantly and rapidly evolving. The evaluation team changed its focus when these new FAA navigation requirements were defined to whether the Loran-C system could meet the rigors of the newly defined required navigation performance (RNP) for a non-precision approach (NPA) [9]. Concurrently, other requirements (e.g., maritime harbor entrance and approach [HEA]) were also evolving [12], [13]. Late in 2002, the evolving HEA requirements were added to the list of application requirements Loran-C had to meet, as were the needs of the time and frequency users of radionavigation systems [14], [15].

1.2 REPORT ORGANIZATION

This report is a synopsis of the extensive work undertaken to determine whether Loran-C can meet the current technical requirements of the various user groups. Section 2 describes the major subsystems of the Loran-C system that are affected by the evaluation, the guiding principles for the evaluation, a means to categorize how GPS outage effects can be mitigated, and a method to categorize the necessary changes to the Loran-C system. Section 3 identifies the current modal criteria for acceptance of the modernized Loran. It should be noted that these criteria differ from the definitions and requirements presented in the current FRP and that some of these definitions and requirements are still evolving. Section 4 provides a high-level overview of the evaluation's approach, the analysis methods, and timing and frequency experiments. In addition, this section describes the results and findings from implementation of these methods. Section 5 describes the embedded communications channel deemed necessary for the system to meet the modal requirements. Section 6 presents the team's conclusions, and Section 7 identifies potential follow-on work if modernized Loran is adopted into the mix of federally provided radionavigation systems.

Appendix A provides information on the organizations and members of the evaluation Team. Appendix B contains a list of the report's commonly used acronyms. Appendix C contains additional information on the technical evaluation and the technical presentations provided to the FAA and the U.S. Coast Guard (USCG). Finally, Appendix D contains a list of references used in the report and a general bibliography of the body of knowledge that also supports the team's findings.

The exhaustive technical detail and in-depth discussion of the multitude of issues and concerns addressed under this comprehensive evaluation are well documented in the extensive body of knowledge that is referenced throughout this report and technical briefs provided to the Department of Transportation (DOT), FAA, and USCG. An interim report was also provided to DOT [16]. In addition, presentations and discussions were held with the technical organizational elements of the various agencies involved with the evaluation. This work refined the requirements for this evaluation and presented additional technical details about the results. This work was accepted by these agencies as part of the justification of the evaluation team's conclusions. The electronic version of this report contains hyperlinks to the electronically available reference material.

2. BASIC EVALUATION INFORMATION

This section describes the major subsystems of the Loran-C system that are affected by the evaluation, the guiding principles for the evaluation, a means to categorize how GPS outage effects can be mitigated, and a method to categorize the necessary changes to the Loran-C system.

2.1 BACKGROUND ON LORAN-C

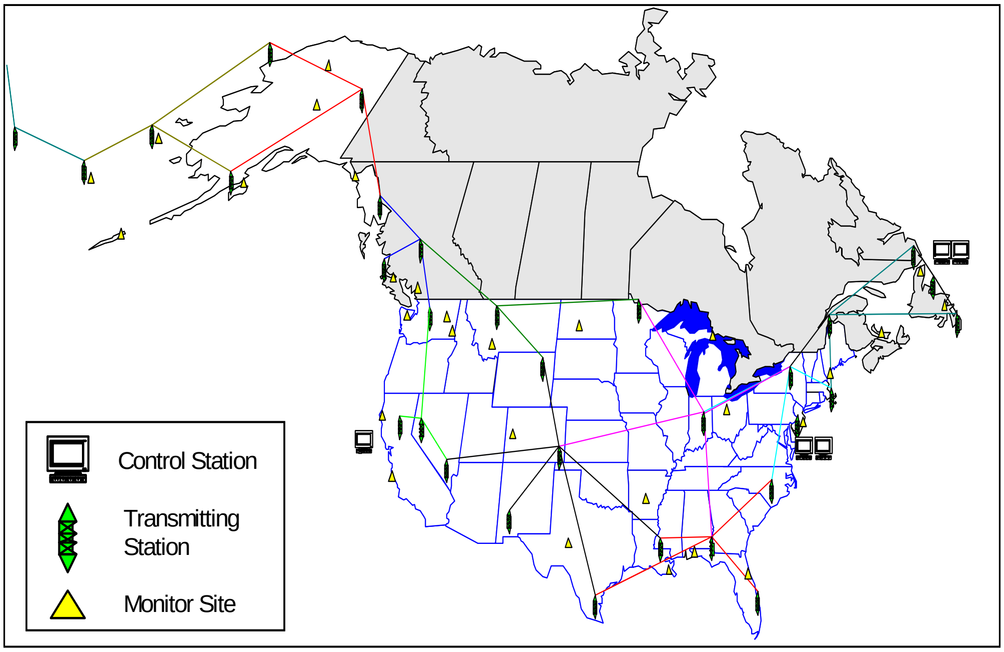
Loran-C is a low-frequency, terrestrial radionavigation system operating in the 90- to 110-kHz frequency band [17], [18], [19]. The U.S. Loran-C system comprises transmitters, control stations, and system area monitors (SAM) (Figure 2.1-1). The Loran-C "chain" is a basic element and consists of between three and six transmitting stations. Each chain has a designated master station and several secondary stations. Some stations have only one function (i.e., to transmit a master or secondary signal in a particular chain), but many transmitters are dual-rated, meaning that they transmit a signal in one chain and another signal for a second chain. The transmitters in the Loran-C chain transmit in a fixed sequence. The length of time in tens of microseconds over which this sequence takes place is termed the group repetition interval (GRI) of the chain. Chains are identified, differentiated, and discussed in terms of their GRI.

The Loran-C transmitters emit pulses of radio frequency (RF) energy at precise instances in time. Position determination is based on the measurement of the difference in time of arrival of these pulses of RF energy. Each master–secondary pair enables determination of one line of position (LOP), measured by the difference in arrival time of the two signals; a minimum of two LOPs is required to determine a position.

Precise timing and synchronization of the Loran-C system are also important, and the Loran-C transmitters incorporate extremely accurate cesium clocks as standard equipment. The Loran-C transmitters need to be synchronized with standard time references. The U.S. Naval Observatory (USNO) provides the time synchronization to Coordinated Universal Time (UTC)[12] for the Loran-C chains.

[12] This report defines UTC to mean UTC as provided by USNO.

Figure 2.1-1. Loran-C System Architecture



The System Area Monitor (SAM) is currently the primary method of monitoring for the Loran-C timing and pulse characteristics. These sites are fixed, unstaffed locations that continuously measure the characteristics of the Loran-C signal as received, detect any anomalies or out-of-tolerance conditions, and relay this information back to the control station so that any necessary corrective action can be taken.[13] These sites are used to ensure that the signal, within the coverage area, is kept within usable limits.

The current Loran-C coverage area is chain based and extends over the entire conterminous United States, most of Alaska, and the coastal waters adjacent to those areas (Figure 2.1-2). Loran-C coverage is also available along the Atlantic and Pacific coasts of Canada; however, coverage over the interior of Canada is extremely limited. Loran-C coverage is also available in the Far East and in northwest Europe. A complementary system, called "Chayka," is operated over the European and Pacific coastal areas of Russia. Although the United States is not directly involved in providing service in these areas of international Loran coverage (with the exception of coverage in the Bering Sea), U.S. Loran-C stations do operate as part of chains that include Canadian and Russian stations.

Loran-C, although primarily a navigation system, also provides users with an extremely stable time reference. Loran-C is, like GPS, a Stratum 1 frequency standard and, by statute, is synchronized to within 100 nanoseconds of UTC.[14]

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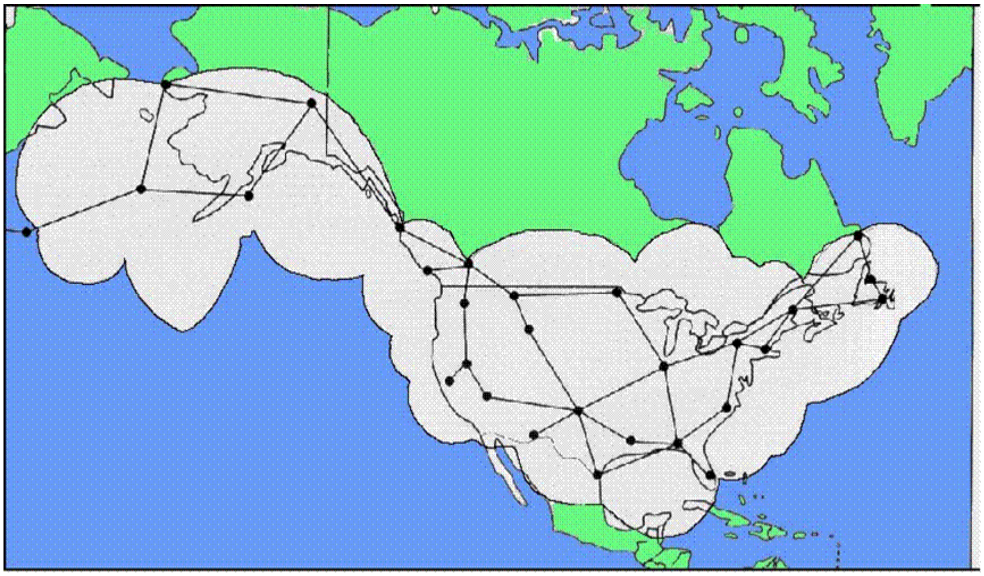
[13] 99.9+ percent of the time the SAM "sees" no abnormalities or out-of-tolerance conditions, but it provides measurements to allow within tolerance corrections to secondary transmission time and clock drift.

[14] Synchronization of Loran-C to UTC is required by PL 100-223, "Airport and Airway Safety and Capacity"

Figure 2.1-2. Existing Loran-C Coverage[15]



2.2 DESIRED RADIONAVIGATION SYSTEM CAPABILITIES

The existing Loran-C system provides supplemental enroute navigation capabilities for aviation users.[16] However, the system's ability to support NPA operations has not been achieved. Similarly, certain marine requirements can be met (e.g., for coastal navigation), whereas others cannot (e.g., HEA). With respect to the time/frequency users, the modernized Loran system could allow for additional applications to continue or recover synchronization during a GPS outage. The use of GPS in these applications is expanding. GPS allows for more effective and efficient operations, so loss in the ability to use GPS and its augmentations will become even more detrimental as these applications expand [3], [10]. Loran-C's value as an alternative system in these cases would vary due to the application and the other available alternatives. The evaluation team adopted the terms *redundant*, *back-up*, and *contingency* to describe Loran-C's capability during a GPS outage [20]. These terms define the level of operational capability that the Loran-C system could provide if there is a GPS service or GPS augmentation system outage—as the capability of a system (e.g., Loran-C) to support a GPS application increases, the chance of an operational disruption due to a GPS outage decreases.

Expansion Act of 1987," December 30, 1987.

15 The figure is from the 2001 FRP and is based on past system parameters and individual Loran-C chain operation.

16 One of Loran-C's strengths is that it provides an area navigation (RNAV) capability, that is, it provides users with their position independent of any point-source navigation aid.

2.2.1 Redundant Capability

With a *redundant capability,* users would experience a seamless transition in process and procedures—there would be no change in operations tempo. This is most desirable because it would result in no impact on operations (e.g., monitors, controllers, or end users). Thus, operational throughput is maintained. For example, in aviation the desire is for NPA. Thus, modernized Loran would provide redundant capability for phases of flight through NPA if it meets RNP 0.3 requirements.

2.2.2 Back-up Capability

With a *back-up capability,* changes in processes would occur due to the different performance capabilities of systems. This would reduce the operations tempo. Operational costs would increase for all phases of the operation. For example, with HEA operations modernized, Loran would provide a back-up capability and, in some areas, a redundant capability if it can meet the HEA requirements.

2.2.3 Contingency Capability

Under a *contingency capability,* a significant reduction in operations tempo would occur. The system would allow for an operation to be safely completed, but new operations or follow-on operations would not be possible (e.g., aircraft could safely land but not take off). At this time, an application’s contingency operations requirements were neither defined nor examined. However, that is not to say that a modernized Loran or Loran-C system would not have this capability.

2.3 GUIDING PRINCIPLES FOR THE EVALUATION

The Volpe GPS vulnerability study identified the need to consider having a redundant, ground-based navigation and timing/frequency capability in-place in case GPS outages occur. Also, the DOT wants to examine the possibilities of using a system used by one operating agency for the needs of another [15]. For many applications, a modernized Loran system could provide an independent source of navigation and timing for GPS applications during a GPS outage. Following are the guiding principles that were used to assess the competing Loran-C options to meet the evaluation criteria:

- Loran-C must have minimal effect on legacy users.
- The system must be internationally accepted and used, which would require—
  - The capability for modifications to be made to the worldwide Loran-C systems [21], [22]
  - Coexistence with a European Loran-C communications method—Eurofix [23].
- Maximum cross-modal benefits are built into the system.
- No or minimal change in spectrum is required for Loran-C.

- Continuity of the service is equally important to all navigation applications but not as critical to precise time and frequency applications.[17]
- Minimal modifications are needed to existing transmitting infrastructure—recapitalize or modify existing infrastructure vice creating a new infrastructure.
- Canadian stations (if required) will use the same equipment and policies as U.S. stations.
- Signal performance parameters are defined at the base of the receiving antenna vice at the base of the transmitting antenna. Properties of the transmitted signal associated with transmitting stations, propagation (including signal and phase distortion), monitor and control stations, receivers, and intentional errors (jamming/spoofing) must be considered.
- Capability will be included as a separate sensor in an integrated navigation and timing/frequency receiver.
- National airspace system (NAS) and airport system certifications will be necessary, as well as an equivalent effort for waterways.
- New receiver specifications for Loran equipment (aviation and marine) must be developed:
  - Use the evaluation results for receiver processing to aid the development of minimum operational performance standards (MOPS) for aviation and marine applications.
  - Adapt existing GPS receiver specifications (e.g., database, user interface).

2.4 TRADE SPACES

From the beginning, the evaluation team hypothesized that a modernized Loran system could meet the requirements of NPA and HEA while improving the services to the timing and frequency community. To prove this supposition, the four major operational parameters—accuracy, availability, integrity, and continuity—had to be analyzed in terms of the application-specific requirements; these parameters are discussed in Section 3.1. The application-specific requirements, although diverse, are interrelated and can be satisfied in many ways (albeit some are more practical or cost-effective than others). To identify, categorize, and decide how best to satisfy the totality of the requirements of the applications, four "trade spaces" were established: radionavigation policy; operational doctrine; transmitter, monitor, and control equipment; and user equipment. After the analyses were completed, these trade spaces were used to describe the modernized Loran system's required characteristics [20], [24]. General definitions for these trade spaces follow.

[17] If the signal does not remain off-air longer than 15 to 45 minutes based on a typical application's internal clock

2.4.1 Radionavigation Policy

The *radionavigation policy* trade space involves areas of radionavigation policy and statements of performance, certification, calibration, funding, and other issues addressed at the policy level. This trade space includes the aspects of the system that require agency, multi-agency, or international action or agreements.

2.4.2 Operational Doctrine

The *operational doctrine* trade space involves areas of operational performance employed in managing and controlling Loran-C operations (e.g., the out-of-tolerance [OOT] limits, control parameters, off-air planning, and other operational-level elements). This trade space describes the changes that operators of Loran-C must integrate into the existing operational control processes and procedures to satisfy all users' requirements.

2.4.3 Transmitter, Monitor, and Control Equipment

The *transmitter, monitor, and control equipment* trade space involves the equipment used for signal generation, monitoring, and control. This trade space describes any modifications to the existing Loran-C infrastructure.

2.4.4 User Equipment

The *user equipment* trade space involves the sensor specification, antenna types, and algorithms used to define and implement user equipment. This trade space describes the parameters and conditions that must be met by the user equipment.

3. BASIC NAVIGATION PERFORMANCE PARAMETER DEFINITIONS AND REQUIREMENTS

The efforts to define and identify the modal requirements for this evaluation were intense and evolved throughout the evaluation, due largely to the development of new technologies that enabled many navigation system improvements. This is most evident in the area of aviation applications and the concept of *required navigation performance* [8]. The definition of the RNP concepts was complemented by the analysis of the GPS WAAS system. The Loran evaluation team adopted the RNP definitions and WIPP's requirements [11], [25]. These definitions and requirements, which are presented in the following sections, differ from those presented in the 2001 FRP, [4].

3.1 PERFORMANCE PARAMETERS

The fundamental performance parameters that describe and define any aviation navigation system are provided in References [4] and [8]. They were the focal point that the evaluation team used in their detailed analyses of Loran system performance. These elements can also be applied to other modal navigation systems. The performance parameters are discussed below.

3.1.1 Integrity

Integrity is defined as the ability of a system to provide timely warnings to users when the system should not be used for navigation [26], [27].

3.1.2 Accuracy

Accuracy is the degree of conformance between the estimated, measured, or desired position or the velocity of a platform at a given time and its true position or velocity. Radionavigation performance accuracy is usually presented as a statistical measure of system error. Accuracy is a statistical measure of performance; therefore, a statement of the accuracy of a navigation system is meaningless unless it includes a statement of the uncertainty in position that applies. Accuracy can be specified in terms of one or more of the following definitions:

- *Predictable.* The accuracy of a position in relation to the geographic or geodetic coordinates of Earth.
- *Repeatable*. The accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigation system.
- *Relative.* The accuracy with which a user can measure position relative to that of another user position of the same navigation system at the same time.

Another factor related to accuracy is fix dimension, which gives "accuracy" more than one measurement axis. The term *fix dimension* defines whether the navigation system accuracy is a linear, one-dimensional line-of-position or a two- or three-dimensional position fix. The ability of the system to derive a fourth dimension (e.g., time) from the navigation signals is also included. A vital factor is a system's ability to limit fix ambiguity. System ambiguity exists when the navigation system identifies two or more possible positions of the user, with the same set of measurements, with no indication of which is the most likely correct position. The potential for system ambiguities should be identified with provision for users to identify and resolve them [7], [26], [27].

3.1.3 Availability

Availability is the ability of the system to provide the required function and performance at the initiation of the intended operation. Availability is also an indication of the system's ability to provide usable service within the specified coverage area. Signal availability is the percentage of time that navigational signals transmitted from external sources are available for use. Availability is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities [26], [27].

A major factor in availability is system capacity given a specified fix rate. System capacity is the number of users that a system can accommodate simultaneously. The fix rate is defined as the number of independent position fixes or data points available from the system per unit time. Another related factor is system reliability, which is a function of the frequency with which failures occur within the system. It is the probability that a system will perform its function within defined performance limits for a specified period of time under given operating conditions. Formally, reliability is one minus the probability of system failure.

3.1.4 Continuity

Continuity is defined as the capability of the total system (comprising all elements necessary to maintain a user's position within the defined space) to perform its function without nonscheduled interruptions during the intended operation. The continuity risk is the probability that the system will be unintentionally interrupted, and not provide guidance information for the intended operation. More specifically, continuity is the probability that the system will be available for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation[18] [28]. The factors that affect availability also affect continuity.

3.1.5 Coverage

Coverage is the result of the preceding four factors. Coverage is the geographic area where the application-specific radionavigation system requirements (e.g., RNP 0.3 or HEA) for integrity, accuracy, availability, and continuity parameters are satisfied at the

[18] *Containment continuity* is the term that applies to RNP RNAV airspace and is the capability of the total system to satisfy the containment integrity requirement without nonscheduled interruptions during the intended operation. Nonscheduled operation is defined as either total loss of navigation capability; a failure of the system that is annunciated as loss of RNP RNAV capability; or a false annunciation of loss of RNP RNAV capability while the system is working properly. Containment continuity is specified by the maximum allowable probability for interruption.

same time. System geometry, signal power levels, receiver sensitivity, atmospheric noise conditions, and other factors that affect signal availability influence coverage. These factors are further discussed in Section 4.

3.1.6 Time and Frequency

The parameters for time and frequency[19] are defined as follows and are presented in Table 3.1-1 [29]:

- *Frequency Accuracy.* Maximum long-term deviation from the definition of the second without external calibration. This is measured as the frequency difference from a recognized and maintained source.[20]
- *Frequency Stability.* Change in frequency over a given time interval.
- *Timing Accuracy.* Absolute offset in time from a recognized and maintained time source (NIST, USNO, BIPM, etc.).
- *UTC.* The international atomic time at USNO (based on cesium-133) with leap seconds added for variable Earth rotation.

Table 3.1-1. Definition of the Stratum Levels

STRATUM	Frequency Accuracy	Frequency Stability	Timing Accuracy
1	$\pm 1.0 \times 10^{-11}$	N/A	N/A
2	$\pm 1.6 \times 10^{-8}$	1.0×10^{-10}/day	N/A
3	$\pm 4.6 \times 10^{-6}$	3.7×10^{-7}/day	N/A
4	$\pm 32 \times 10^{-6}$	Not Spec'd	N/A

3.1.7 Interrelationship of Parameters, System Characteristics, and Applications

In many instances, the characteristics of the Loran-C system affect all or some of the above performance parameters (e.g., the signal-to-noise ratio [SNR] affects accuracy and integrity). Also, a characteristic may affect different parameters in different ways (e.g., the number of stations available to determine a fix may improve accuracy but may reduce integrity). In addition, the impact of a performance parameter and system characteristic may differ from user community to user community requirement (e.g., accuracy is the determining parameter for HEA, but integrity is the determining parameter for NPA). These interrelationships and other possible interrelationships among performance factors, system characteristics, and user applications were analyzed to determine the best trade space solution that met all the performance requirements of each application.

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19 Frequency is in hertz (Hz).

20 For example, these sources could be the U.S. Naval Observatory (USNO), National Institute Standard and Technology (NIST), or Bureau International des Poids et Mesures (BIPM).

3.2 MODAL REQUIREMENTS

Table 3.2-1 summarizes the performance characteristics of Loran-C as found in Reference [4].

Table 3.2-1. FRP 2001 Loran-C System Performance

2 drms[21] Accuracy		Availability	Coverage	Fix Reliability	Fix Rate	Dimension	System Capacity	Ambiguity Potential
Predictable	Repeatable							
0.25 NM (460 m)	60–300 ft (18–90 m)	99.7%	CONUS AK Selected Overseas Areas	99.7%	10–20 fix/sec	2D + Time	Unlimited	Yes, Easily Resolved

The current state of the evolving modal requirements that modernized Loran must meet is discussed in the following paragraphs.

3.2.1 Aviation Requirements

From the FAA murder board [9] and as described in the team's interim evaluation report [16], the team concluded the requirement for NPA was RNP 0.3, which equates to the following requirements shown in Table 3.2-2.

Table 3.2-2. Aviation RNP 0.3 Requirements

Performance Requirement	Value
Accuracy (target)	307 meters
Monitor Limit (HPL) [22] (target)	556 meters
Integrity	10^{-7}/hour
Time-to-Alert	10 seconds
Availability (minimum)	99.9%
Availability (target)	99.99%
Continuity (minimum)	99.9%
Continuity (target)	99.99%

3.2.2 Marine Requirements

Using the work of the International Maritime Organization (IMO) [12] and the USCG's Harbor Entrance Approach studies[23] [30], [31], [32], the evaluation team interpreted the requirements for harbor entrance approaches at the levels presented in Table 3.2-3.

[21] The 2-drms (twice distance root mean square) statistical error refers to the radius of a circle, centered at the true position that contains at least 95 percent of the measured or estimated positions.

[22] HPL is horizontal protection limit.

[23] The referenced USCG Harbor Entrance and Approach Study introduced a rigorous alternative approach to marine requirements, known as the Target Level of Safety (TLS) technique. Although not used in defining these parameters, its use could be considered in discussing trade space alternatives should HEA performance not be met in a desired area.

Table 3.2-3. Maritime Harbor Entrance and Approach Requirements

Performance Requirements	Value
Accuracy (back-up)	20 meters, 2 drms
Monitor/Alert Limit (back-up) [24]	50 meters, 2 drms
Integrity (target)	3×10^{-5}/hour
Time-to-alert	10 seconds
Availability (minimum)	99.7%
Continuity (minimum)	99.85% over 3 hours

3.2.3 Time and Frequency Requirements

The timing and frequency users have no known published government requirements that equipment must meet. However, timing and frequency applications, including those used by government agencies, employ applications with specific timing and frequency requirements. The evaluation team used information from the DOT Task Force Report to help define the time and frequency requirements, which are summarized in Table 3.2-4 [15]. Also, the evaluation team surveyed industry for their desired performance metrics. The comments from T1X1, a standardization committee within the timing/frequency community, provided information for a range of frequency and timing users. This information was used in the evaluation [14].

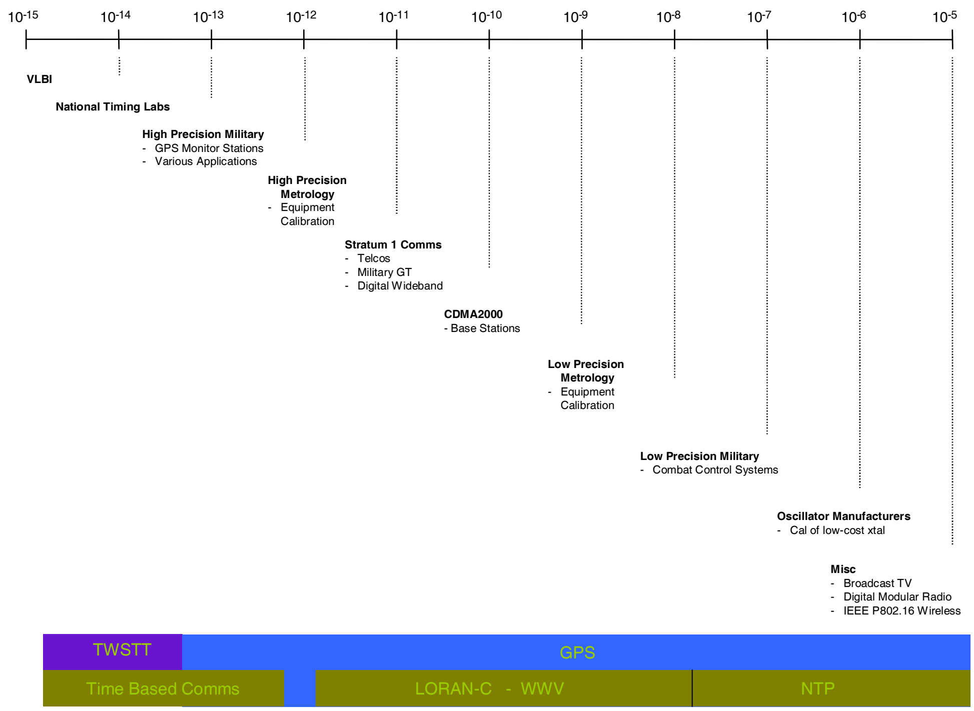
Table 3.2-4. Time and Frequency Requirements

Performance Requirement	Value
Frequency Accuracy (target)	1×10^{-13} averaged over 24 hours
Frequency Accuracy (desired)	1×10^{-12} averaged over 6 hours
Frequency Accuracy (minimum)	1×10^{-11} averaged over 1 hour
Antenna	No External Antenna (desired)
Legacy Use	Backward Compatibility (desired)
Integrity Data	Minimum “Use/No Use” flag
Timing Data	Time Tag, Leap Second Info
Timing Accuracy at the user’s receiver	< 100 nsec (RMS)
Differential Data Update Rate	< once/hour

Figure 3.2-1 and Figure 3.2-2 depict the current applications as a function of the performance requirements, as well as the typical method of how the performance is met. The figures show a gap in each community where GPS is the only radionavigation system that can provide services. The team focused its analysis on these gaps to determine whether modernized Loran could provide a viable alternative to GPS in the event of a GPS outage.

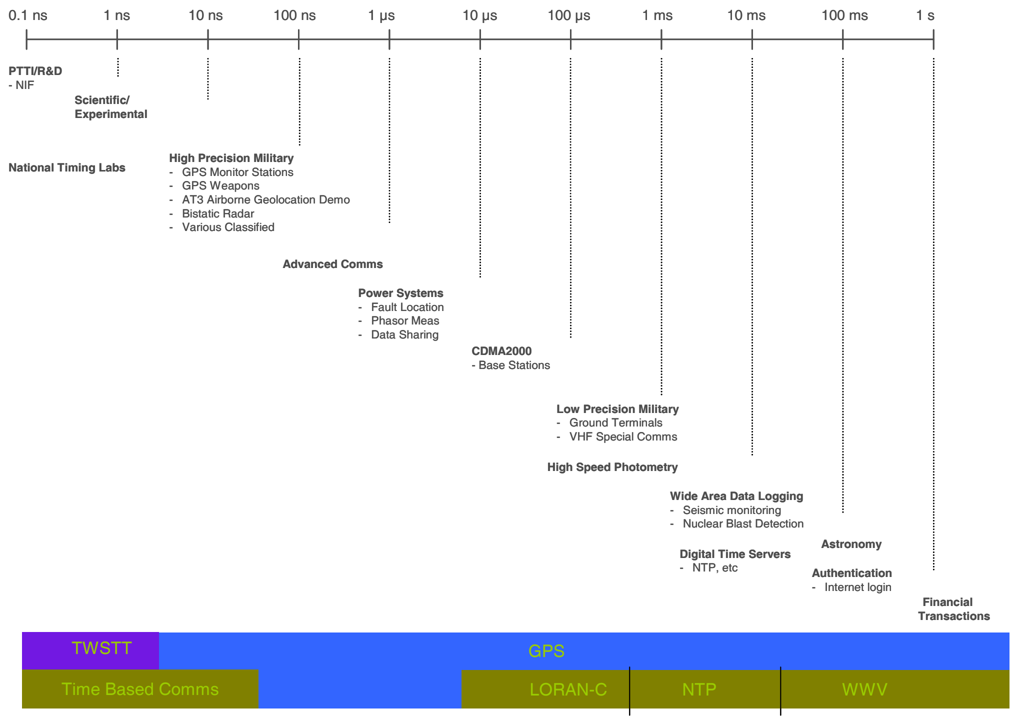
[24] Monitor limit is similar to horizontal protection limit (HPL).

Figure 3.2-1. Frequency Users and Their Applications[25]



[25] TWSTT is two-way satellite time transfer.

Figure 3.2-2. Timing Users and Their Applications



3.2.4 Land Requirements

Numerous land applications (e.g., vehicle, asset, animal, and human monitoring or tracking applications) used Loran-C before the general availability of GPS [4], [33], [34]. Loran is still viable for these applications, especially for critical or high-economic value applications where there would be a safety, security, or economic benefit in having a system available when a GPS outage occurred (e.g., tracking hazardous cargo). However, before these applications and Loran's use can be evaluated, the specific requirements must be identified and validated.

4. EVALUATION PROCESS AND RESULTS

The FAA determined that for modernized Loran to have a role in the future mix of aviation radionavigation systems, it needed to meet the requirements for NPA. The major performance factor in this application was determined to be integrity. This spawned the creation of the Loran Integrity Performance Panel (LORIPP). This panel had similar purposes and process to that of the WIPP [11]. Maritime and timing/frequency requirements came under reexamination in response to the Volpe vulnerability study [3] and other documents, for example References [2], [15], and [35],[26] and the events of 9/11. These documents recommended that alternative sources for navigation and timing should be identified, studied, and, where applicable, adopted. The prime area of interest in the maritime arena was to determine whether modernized Loran could provide redundant or back-up capabilities in HEA operations. The ability to do so demands at least an order of magnitude improvement in accuracy over those for aviation NPA operations and coastal maritime navigation. The LORIPP determined that the aviation integrity methodology could be readily adapted to HEA requirements. This prompted formation of the Loran Accuracy Performance Panel (LORAPP) to focus on the special accuracy needs of HEA.[27] The results related to timing and frequency applications were outcomes of the LORIPP and LORAPP efforts. The analysis discussed herein focused primarily on the conterminous United States. Alaska presents a very different radio propagation environment, and different measures may be required to mitigate early skywave effects in this state. The technical team has studied this issue, but schedule has prevented a complete analysis. However the methodology described herein can readily be applied in Alaska.[28] A brief description of Alaskan coverage is discussed in Appendix C and the papers listed in Appendix D.

4.1 APPROACH

The approach that the evaluation team adopted centered on answering the question: "Can Loran-C be used to mitigate the effects of a GPS outage?" Following the WIPP model, the first step in finding the answer was to assemble a group of experts in navigation methods, in Loran-C, in the navigation requirements, and in the method developed under the WAAS GPS effort to establish how the requirements could be met. The formation of the LORIPP was the first step taken. The next steps are described, herein. *It is important to note that this evaluation did not include a comparison of other systems that could meet the modal requirements. If any comparison is done, the system should be evaluated using methodology similar to the WIPP processes [11]*. This approach is illustrated in Figure 4.1-1.

The LORIPP translated the general performance requirements for RNP 0.3 operations into Loran-specific terms. As an example of the LORIPP's process, the 10-second time-

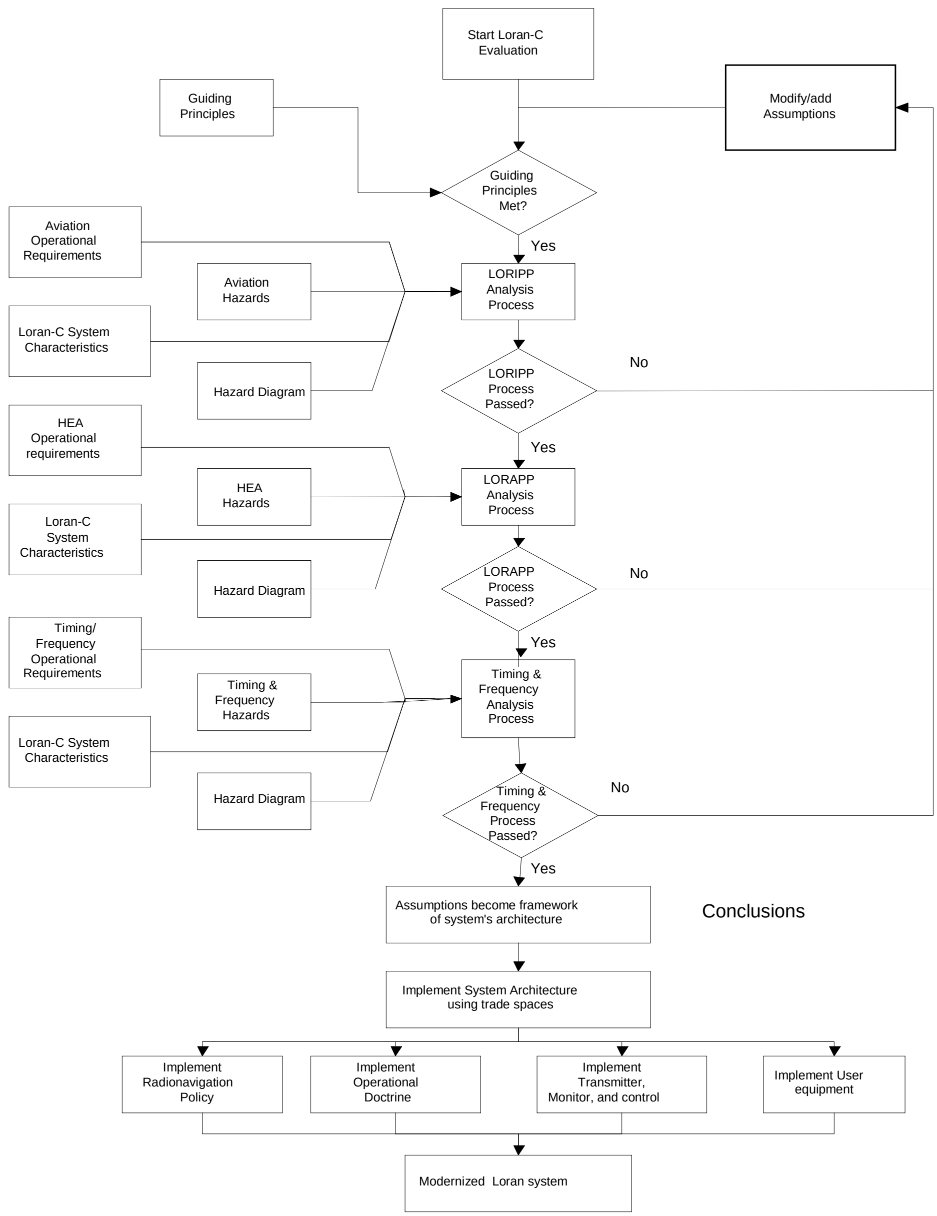
[26] The 1998 Booz Allen Report to Congress noted that the 1997 President's Commission on Critical Infrastructure Protection advised caution until GPS vulnerabilities were better understood. Specifically, the Commission recommended that the government, "Fully evaluate actual and potential sources of interference to, and vulnerabilities of, GPS before a final decision is reached to eliminate all other radionavigation and aircraft guidance systems."

[27] The HEA requirements are still evolving.

[28] Loran-C coverage in Alaska is briefly discussed in Appendix C and papers listed in Appendix D.

to-alarm requirement was examined in terms of transmitted signal integrity and receiver processing requirements under such conditions as signal blink or off-air.[29] This in turn established a minimum SNR, which began the process of composing a coverage model.

Figure 4.1-1. Block Diagram of the LORIPP Evaluation Process



29 Blink versus off-air: Blink is an indication that the master or secondary signals in a Loran-C chain are out of tolerance and not to be used. Loran-C receivers have a blink alarm that warns the user that the indicated position may not be reliable. A blink condition warns that the signal power or phase is out of tolerance or that an improper phase code or GRI is being transmitted. During blink, the Loran-C signal is still being transmitted albeit in a different format. Off-air is when the signal is not transmitted. From a signal-to-noise ratio (SNR) perspective, off-air is easier to detect.

As additional requirements and elements of the coverage model were considered, the team began to compile a list of hazards that threaten the ability of the system to meet one or more of the requirements. For example, uncertainty about the value of the additional secondary factor (ASF)[30] can create accuracy and integrity bound values that exceed the maximum values allowed for RNP 0.3. This uncertainty has a spatial component that describes signal variations from one location to another. It also has a temporal component that describes variation over time. The effects must be translated into a form that allows comparison to the parameters stated in the requirements.

As seen in Figure 4.1-1, the LORIPP process was iterative. As problems arose, alternative system solutions were found and the system was reevaluated in light of those solutions. For example, the team found that current Loran-C could not meet the accuracy for requirements for HEA. In such cases, practical mitigation methods (e.g., a harbor ASF survey) were identified, and their effects modeled [36], [37], [38]. As the process unfolded, the team identified changes in individual requirements for the modernized Loran system that collectively satisfy the operational requirements. The most convenient means of tabulating these performance requirements is in the form of variations to existing system specifications. These are identified as a list of assumptions upon which the performance model is based. The final result for the aviation RNP analysis is a set of predictions, in the form of coverage diagrams, along with a description of the hazards that were identified and the assumptions about how the system will be operated. For the HEA applications, additional hazards and assumptions led to additional coverage diagrams based on the different requirements. These aspects of the evaluation approach are described in the following sections.

4.2 ASSUMPTIONS

As indicated above, the LORIPP approach was implemented in an iterative fashion. As the process was executed, a number of threats to system performance were identified. Mitigating factors or assumptions were identified and can be divided into the four general trade spaces:

- Radionavigation policy
- Operational doctrine
- Transmitting, monitoring, and control equipment
- Receiving equipment.

The LORIPP examined the assumptions relating to receiving equipment and transmitting, monitoring, and control equipment through analysis, simulation, or actual implementation. The assumptions were determined to be both practical and feasible to implement. The LORIPP and the Loran-C system operators also examined the operational policy and procedural assumptions and determined that they are both practical and feasible. When validated, these assumptions provide a detailed description

[30] ASFs are land path factors that account for the speed of propagation of Loran-C signals over land compared with seawater. If not accounted for, variation of propagation velocities over land degrades the absolute accuracy of the Loran-C system but does not affect the repeatable accuracy.

of the modernized Loran system's characteristics. The validated assumptions and the references that support their validation are listed below.

4.2.1 Radionavigation Policy Assumptions

Radionavigation policy and, more specifically, the Federal Radionavigation Plan, will address and commit to the following assumptions:

- If required, the Canadian stations will be equipped and operated in the same fashion as the U.S. stations. (Appendix C)
- The Federal Government will conduct airport calibrations that yield ASF and ECD[31] values to be used during RNP 0.3 approaches along with bounds on the errors associated with these parameters. (Appendix C and Section)7.2.1
- The Federal Government will conduct HEA channel surveys that yield ASF and ECD values to be used in the channel along with bounds on the errors associated with these parameters. (Appendix C and Section7.2.2)

4.2.2 Operational Doctrine Assumptions

The following assumptions pertain to system operations. In addition to the provided references, these items must be addressed in operations and support policies.

- The current method of starting blink when a signal abnormality is detected will be replaced by the method of taking the station off the air. (Appendix C, Reference [39] and revision to References [17], [18], and [19])
- The method of controlling the Loran-C signal will change from SAM control to time of transmission (TOT) control.[32] (Appendix C, Reference [40] and revision to References [17], [18], and [19])
- Long-term synchronization to UTC will be maintained via a primary and secondary method with at least one method being independent of GPS. (Appendix C, References [41] and [42] and revision to References [17], [18], and [19])
- Small phase corrections will be performed as a continuous process instead of in discrete steps (noted in Section 4.4.1). (Appendix C, Reference [41], [42], [43] and revision to References [17], [18], and [19])
- Maintenance periods will be limited and planned to minimize the effects on continuity and availability. For example, there will be no concurrently scheduled off-airs within the same coverage area. (Appendix C and revision to References

[31] ECD, or envelop-to-cycle difference, in basic terms, is the time relationship between the phase of the Loran-C signal and the time origin of the envelope waveform.

[32] Under the current method of control, the system area monitor (SAM) sites are used to observe the transmitted signal (signal strength, time difference, and pulse shape) for a particular baseline as received in the coverage area. The information from this monitoring point is used to control the transmitted signals. TOT control maintains a constant time of transmission at the transmitting station as referenced to UTC.

[17], [18], and [19])

- Every attempt will be made to schedule off-airs during morning daylight (local time). (Appendix C, References [44], [45], and [46] and revisions to References [17], [18], and [19])
- Stations will be staffed to ensure that the current level of availability is met by the system. (References [5] and [47]) Users will be notified of planned outages. (Appendix C and revision to References [17], [18], and [19], as appropriate) The automatic blink system (ABS) tolerance will be no greater than 100 nsec. (Appendix C, Reference [48] and revisions to References [17], [18], and [19])
- Transmitter switches (i.e., changes from the operational transmitter to the standby transmitter) will be minimized. (Appendix C and revisions to References [17], [18], and [19])

4.2.3 Transmitting, Monitoring, and Controlling Equipment Assumptions

The following assumptions pertain to the transmitting, monitoring, and controlling equipment of the system. In addition to the provided references, these items must be addressed in operations and support policies. This is envisioned to be in the form of changes to the infrastructure's maintenance procedures and specification for the Loran signal, as well as other documents provided to industry and the user communities:

- The Loran-C signal format will remain the same. (Appendix C and revisions to References [17], [18], and [19]) All stations may be dual rated. (Appendix C, Reference [49] and revisions to References [17], [18], and [19])
- All tube transmitters (TTX) will be replaced with solid-state transmitters (SSX) and the older versions of the SSXs will be updated to the new SSX standards. (References [5], [7] and [50] and their updates)
- New time and frequency equipment (TFE) will be installed. (Reference [5] and [7])
- New cesium clocks will be installed. (Reference [5] and [7])
- New TCS and RAIL[33] units will be installed. (Reference [5] and [7]) Momentary off-airs[34] will be reduced to 3 seconds or less. (Reference [7] and revisions to References [17], [18], and [19])
- Non-scheduled unusable incidents of greater than 3 seconds in duration will be reduced to no more than 20 per station, per year. (Appendix C and revisions to References [17], [18], and [19])

[33] The transmitter control set (TCS) and remote automated integrated Loran-C (RAIL) equipment allows for the monitoring and control of all station equipment at a central facility to reduce the number of personnel assigned to specific locations.

[34] Momentary off-airs are short duration outages of a station's Loran-C transmission. They are typically the result of a switch (planned or unplanned) of the redundant sections of the station's transmitting equipment suite.

- ECD will continue to be monitored and controlled in real time at the transmitting station but to a tolerance of 200 nsec. (Appendix C and revisions to References [17], [18], and [19])

- When the parameters are out-of-tolerance (OOT), an alarm (an off-air rather than blink) should be detected and transmitted within 2 seconds. (Appendix C and revisions to References [17], [18], and [19])

- The probability of a failure to issue the alarm, given there is an OOT condition, will be less than 10^{-8}. (Appendix C and revisions to References [17], [18], and [19])

- A 9th pulse in each GRI will be broadcast by all stations. It will be modulated to provide differential corrections for maritime and time/frequency applications, as well as station identification and integrity (i.e., early skywave detection) for aviation. (Appendix C; Section 5; Reference [51]; and revisions to References [17], [18], and [19])

- A monitoring network will be established for maritime differential corrections and far-field propagation effects. The network will include current SAM sites, Loran-C stations, and additional monitor sites as necessary for a given harbor. (Appendix C; References [49] and [52]; and revisions to References [17], [18], and [19])

- SAM sites will be retained for monitoring propagation in the far field (e.g., skywave [35] [53]). (Appendix C; Reference [54]; and revisions to References [17], [18], and [19])

- Some SAM sites will have a high accuracy clock for synchronization to UTC to provide time and frequency corrections for common-view timing. (Appendix C; Reference [41]; and revisions to References [17], [18], and [19])

- Modulation of the transmitted signal will have minimal effect on navigation performance. (Appendix C [9], and revision to References [17], [18], and [19])

- Power interruption will not occur in the event of a commercial power failure. (Appendix C; References [7] and [50]; and revisions to References [17], [18], and [19])

- Output power fluctuations will not exceed 5 percent. (Appendix C and revisions to References [17], [18], and [19])

- TFE will support three kinds of phase adjustments (PA): Local PAs (LPA) are entered by an operator and take place over long period of time. Instantaneous local LPAs (ILPA) are discrete steps entered by an operator and take place instantaneously. Automatic PAs (APA) are entered without operator intervention by the TFE control loop and take place over long period of time. (Appendix C; Reference [41]; and revisions to References [17], [18], and [19])

[35] This skywave warning will be transmitted via the 9th pulse

4.2.4 User Equipment Assumptions

The following items pertain to the user equipment for the system. In addition to the cited references, these items must be discussed in terms of detailed receiver specifications. This is envisioned to be in the form of user-community-specific MOPS for the equipment. The changes are as follows:

- Equipment will operate in the all-in-view mode (cross-chain, master-independent) reading and applying 9th pulse information, as appropriate, to the user's application. (revisions to References [55] and [56])
- Aviation equipment will use H-field or equivalent antennas for which the maximum specified precipitation static (p-static) results in less than 40 dB/µV/m equivalent noise (30 kHz bandwidth). (Appendix C, References [57] and [58], and revisions to References [55] and [56])
- Equipment must verify cycle identification via an all-in-view method comparable to the LORIPP model. (Appendix C; Reference [59]; and revisions to References [55] and [56])
- Equipment will comply with a modernized Loran signal specification and operational doctrine. (revisions to References [18], [19], [55], and [56])
- Equipment must be able to "coast" through a 3-second outage (e.g., due to a transmitter switch). (Appendix C; Reference [39]; and revised References [55] and [56])
- Equipment will be designed to meet an 8-second time-to-alarm[36] requirement at minus 10 dB Gaussian noise equivalent SNR, with the possibility of one 3-second "momentary off-air" in any 10-second interval, and with a false alarm rate less than 10^{-4}, with a missed detection probability of less than 10^{-8}. (Appendix C and revisions to References [55] and [56])[37]
- Equipment must achieve results comparable to at least 12 dB processing gain at the 99th percentile level of atmospheric noise. (Appendix C; References [60] and [61]; and revisions to References [55] and [56])
- Equipment must be able to use government-provided ASF and ECD information. (Appendix C and revisions to References [55] and [56])
- Equipment must process cross-rate interference in a way that yields performance comparable to the LORIPP model. (Appendix C and revisions to References [55] and [56])
- Equipment must be able to meet a MOPS certification for the associated application (aviation, marine, timing). (Appendix C and revisions to References [55] and [56])

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[36] This allots 2 seconds of the 10-second time-to-alarm to the transmitter portion.
[37] This is primarily navigation requirement and may not be applicable to timing/frequency applications.

4.3 General Considerations

Four general considerations should be mentioned before hazards are discussed:

- The distinction between cycle and phase integrity
- The requirement to treat bias errors differently from random errors
- The relationship between accuracy and integrity performance parameters
- The treatment of the four parameters in the analysis and model.

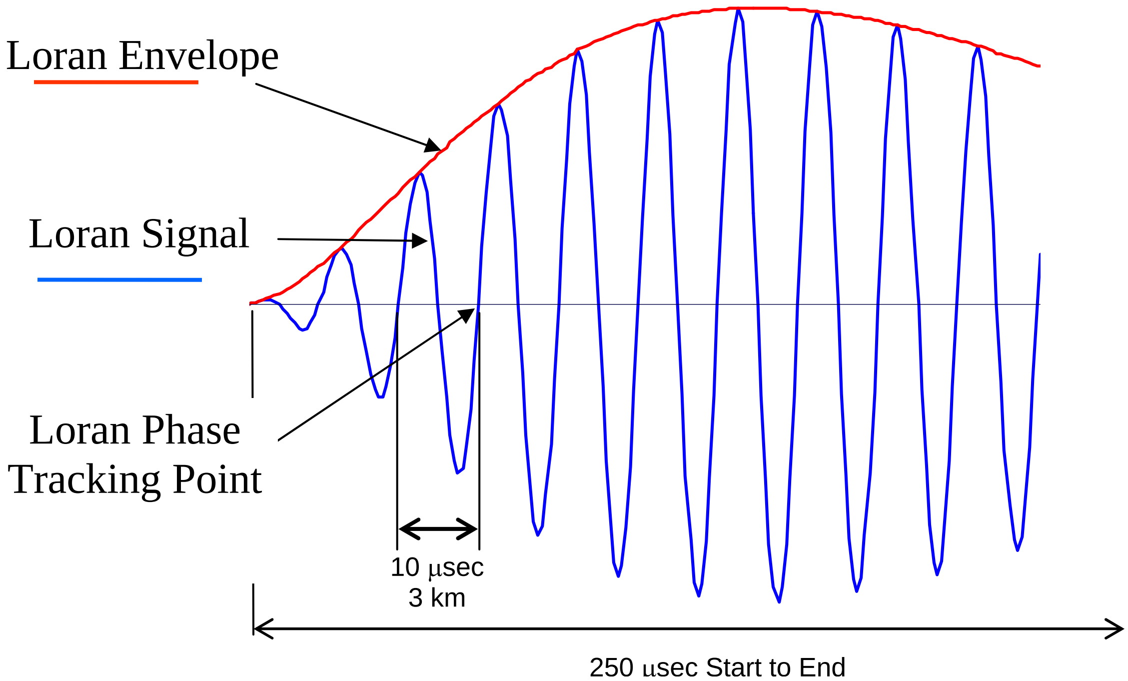
Each topic is discussed below.

4.3.1 Cycle Versus Phase Integrity

In the operation of the original Loran system, eventually designated Loran-A, signal time-of-arrival measurements were determined by the pulse shape or envelope. Subsequent successful versions of Loran evolved from the early 1950s U.S. Air Force (USAF) project to develop “cycle matching Loran,” which we now call Loran-C. These versions were based on the time of arrival measurements on the “carrier,” that is, the cycles within the pulse envelope.

In modernized Loran, the envelope, or pulse shape (see Figure 4.3-1) is still used but only to allow the receiver to select a consistent cycle of the carrier to track. Because the 100 kHz carrier signal has a period of 10 microseconds (µsec), a cycle error on a given signal will cause the arrival time measurement for that signal to be in error by an integer multiple of 10 µsec. This corresponds to a multiple of 3 km. This creates a high probability that the position error would exceed the allotted 556 meter RNP 0.3 error. Thus, the LORIPP model treats a cycle selection error as a hazard that requires a signal to be eliminated from the position fix if the model does not have adequate confidence that the correct cycle is selected.

Figure 4.3-1. Loran-C Pulse Shape



This causes the integrity part of the analysis to have two distinct components: one for cycle integrity and one for phase integrity. Because cycle and phase integrity are both necessary to ensure the integrity of the Loran-C solution, the process has two steps.

1. *Cycle.* A receiver (which the coverage model emulates) must determine and track the correct cycle for each signal to the desired level of integrity.

2. *Phase.* Given the correct cycle selection for all signals that will be used, the model uses estimates of bounds on the phase errors for each signal to compute the horizontal protection limit (HPL) of the resulting position fix.

If the Loran-C system is to be considered available for the application, the HPL must be maintained within the specified limit (e.g., 556 meters for RNP 0.3) at a probability sufficient to yield overall (cycle and phase) integrity at the desired level (one part in 10^7 for aviation). Some of the hazards listed in Table 4.4-1 (see Section 4.4) will affect only one of these two components; many will affect both cycle and phase.

4.3.2 Random Versus Bias Errors

An important element of the methodology is to distinguish between bias errors and errors that rapidly fluctuate. For many systems, the distinction is obscure. However, for Loran-C, it is fairly well known via the distinction between absolute accuracy and repeatable accuracy.[38] The bias can be constant or slowly varying.[39] Using concepts similar to WIPP's, the LORIPP used the following definition: If the variations in some component are rapid enough that they would be averaged out by a receiver, they can be treated as a random component. If, instead, variations are so slow that, for example, the component would remain essentially constant over the 150-second duration of a typical non-precision approach, that component must be treated as a bias. This is important because the mathematical effects of the bias components generally lead to much larger position errors than random errors of the same size.

One exception to this rule involves correlated bias errors. These are manifested for Loran-C in the form of seasonal variations in the signal propagation speed. The effects on the predicted system performance are much better if it can be proved that many components are correlated—or at least random. Thus, when LORIPP investigators studied each hazard, care was taken to determine not only the size of the hazard but also whether all or some portion of the hazard could be modeled as random or as correlated effects.

4.3.3 Accuracy Versus Integrity

The integrity performance parameter includes the time-to-alarm specification. The rest of integrity is defined by the horizontal protection limit that has units of meters. Integrity is, therefore, related to accuracy, which is also specified in units of meters. A first-order view is that the HPL of 556 meters for RNP 0.3 is, at the "seven 9s" level (i.e., one part in 10^7), a 5.33 sigma statistic were it a zero-mean Gaussian random variable. By contrast, the 307 meters for RNP 0.3 accuracy is for 2-drms that would be a 2-sigma statistic were it a zero-mean Gaussian random variable. For the first order, the ratio of the requirements is 307/556, or 0.55. The ratio of the statistics is 2/5.33 or about 0.375. The question could be translated as follows: "If the HPL requirement is satisfied, is a statistic that is 37.5 percent of the HPL statistic likely to give a result that is less than 55 percent of the HPL result?"

The answer is "yes" for a zero-mean Gaussian random variable. However, it is known that Loran-C has substantial biases. Rare examples can even be found in which these biases can result in achieving the 556-meter HPL but missing the 307-meter accuracy requirement—if accuracy were calculated according to the same rules used to calculate HPL. However, for calculating accuracy, the rules change.

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[38] This is often portrayed as a "scatter plot" of Loran-C position fixes obtained, say, every minute over a several hour period. A plot calibrated with an accurate reference system would often show all the fixes contained within a circle of radius 20 meters. However, the center of that circle might be 200 meters offset from the true location. The 20-meter radius is a measure of the repeatability (over the few hours), and the 200-meter offset is a measure of the bias.

[39] For example, in the Rocky Mountain area with a 200-meter position bias, the error remains just about 200 meters, day and night throughout the year. By contrast, in the northeast United States the greater density of the lower atmosphere allows signal propagation characteristics to vary significantly as temperature varies over the course of a year. The bias might be 200 meters to the east of a user's true location in the summer but, on average, 150 meters to the southeast of a user's true location in the winter.

Specifically, for accuracy, most of the components combine in a root-sum-square manner and can be averaged over time. As a counter example, a system might meet the HPL requirement at a given location with 0.99999985 probability in July, but 0.99999995 in August is not a "seven 9s system." For integrity, averaging those two numbers is not permitted. For accuracy, averaging is permitted.[40]

With this change in rules, the LORIPP found that for RNP 0.3, meeting the HPL requirement guarantees that the accuracy requirements are met. Accordingly, the LORIPP considers the model to be complete even though it does not specifically address accuracy.

For the HEA application, the biases will be significantly reduced. The HEA calibration will be much more comprehensive than the airport calibration—virtually every part of the channel will be measured and the spatial ASF bias component will be nearly eliminated. Similarly, the differential monitors will eliminate most of the temporal biases. Accordingly, the HEA model approach will actually model the accuracy.[41]

4.3.4 Availability and Continuity

Although there are four performance requirements, both the RNP and HEA analyses and models are driven primarily by one requirement. As previously established, the accuracy requirements are met for RNP 0.3 when the integrity requirements are met. The situation is reversed in the HEA application. Thus, one of the four parameters that must be separately calculated is eliminated. The elimination of the other two is addressed first by asking, regarding availability, "availability of what?" For aviation purposes, the answer is "availability of a navigation capability that meets both the integrity and accuracy requirements." Regarding continuity, it is a conditional availability computed over the duration of an operation. Again, this means "conditional availability of a navigation capability that meets both the integrity and accuracy requirements."

Thus, the analysis focuses on integrity and accuracy. If, for example, atmospheric noise is set at the 10^{th} percentile level, then every location in the lower 48 states can track enough signals with small enough errors to meet the integrity and accuracy requirements. When that noise level is increased, problems start to occur in some well-known areas, such as near Jupiter, Florida, in a small portion of southern New Mexico, and in a small area in northern Minnesota. Until well above the 90 percent noise level, these problem areas only grow slowly.

Eventually, the noise level is increased above the 99.9 percent level and availability statements can be made. For any given location, it is a tabulation of what happens to

40 A good explanation for this change in rules is recognizing that accuracy is specified at about the 95 percent level. Nineteen successes out of twenty trails is not a safety-of-life performance metric. This success rate, however, can be a transportation efficiency specification. In such a case, if the goal is to save an average of 100 gallons of fuel per flight, that goal is achieved even if only 90 gallons per flight were saved in July, but 110 gallons per flight were saved in August.

41 It is important to note that the equivalent of the HPL limit in the HEA is 2.5 times the accuracy limit. With the biases essentially eliminated, the dominant error terms are closely approximated as zero-mean Gaussian random variables and this ratio makes the two parameters track together.

integrity and accuracy. Continuity differs somewhat in that some of the hazards must be modeled differently because continuity is really a measure of disruptions over short periods. The calculation methods are somewhat different, but the basic approach is that everything revolves around integrity and accuracy calculations. Recognition of this characterization helps provide an understanding of how the hazards are defined and how the model treats them.

4.4 HAZARDS TO LORAN

A hazard to Loran is anything that can adversely affect the signal to produce improper navigation information. Hazards can be divided into three categories based on where their effects are manifested:

- At the Loran transmitters
- Along the propagation path
- At the user receiver.

Each hazard will affect at least one of the system performance factors: integrity, accuracy, availability, or continuity. A brief description of each hazard is provided in the following sections. Table 4.4-1 summarizes the hazards.

Table 4.4-1. Hazards and What They Affect

Category	Hazard
Transmitter	Timing and frequency equipment Transmitter and antenna coupler Transmitter equipment monitoring
Propagation	Spatial variation of phase along approach path Temporal variation of phase Spatial variation of ECD along approach path Temporal variation of ECD Temporal variation of SNR
Receiver	Platform dynamics Atmospheric noise Precipitation static Skywaves Cross-rate interference Man-made RFI Structures Receiver calibration

4.4.1 Transmitter Hazards

The signals can be monitored and controlled to within certain tolerances that are used in the analysis models discussed in Section 4.6 and 4.8 to determine system performance as seen by the user.

The aviation requirement for integrity is that an integrity failure will not occur with a probability of more than one part in ten million (i.e., 10^{-7}) per hour, whereas the maritime requirement is that the probability of such a failure will be no greater than three parts in one hundred thousand ($3x10^{-5}$). Thus, the transmitting station signal generation and monitoring equipment is designed to ensure that these tolerances are achieved with a probability of one part in one hundred million (10^{-8}).[42] This is a critical step in the LORIPP analysis because it establishes that the signal generation and monitoring equipment, not the user receiver, is required to detect an error in the transmitted signal due to the transmitter hazards.

The tolerances relate to parameters that apply to three major divisions of the station equipment—the timing and frequency equipment, the transmitter and antenna coupler, and the monitoring and control equipment. A brief description of each follows.

4.4.1.1 Timing and Frequency Equipment (TFE)

The timing and frequency equipment establishes the reference phase, or time of the transmission. An "ensemble clock" of three high-quality cesium-based frequency standards is used to produce the short-term accuracy of the timing reference. Time transfer methods are used to steer all the transmitting stations' time references to a common standard (i.e., UTC) via GPS.[43] The ensemble clock maintains high accuracy for short-term GPS outages. For a redundant capability in the case of a GPS failure, long-term averages of reciprocal path Loran measurements at each transmitting station will be used to establish "Loran time."[44] Either method will satisfy all navigation, timing, and frequency synchronization requirements.

4.4.1.2 Transmitter and Antenna Coupler

The high-power components of the signal generation equipment historically produce hazards to system performance known as momentary transmission interruptions that greatly reduce continuity performance. They are also the source of more than 95 percent of the longer-term interruptions that limit system availability. Equipment imperfections create discrepancies between the precise timing reference and the phase of the radiated signal and deviations from the desired signal shape, as measured by the ECD parameter. Along with improved station power systems and certain user receiver modifications, the new equipment will eliminate the effects of momentary transmission interruptions and reduce the total number of signal outages. The new equipment will significantly reduce transmitted phase and signal shape imperfections. The LORIPP has established tolerances for these hazards that are included in the performance model.

4.4.1.3 Transmitter Monitoring and Control Equipment

Both the timing and transmitter systems have internal controls that provide a level of integrity. In addition, the transmitting station has an overall control system that has been upgraded. The remote automated integrated Loran-C (RAIL) system monitors and controls all the transmitting equipment within the station. The automatic blink system

[42] Transmitter availability is studied by examining the historical failure rates and changes due to upgrades in the station equipment

[43] Synchronization of Loran-C to UTC is required by PL 100-223, "Airport and Airway Safety and Capacity Expansion Act of 1987," December 30, 1987. Like GPS, Loran-C is a Stratum 1 timing standard.

[44] This redundant capability is accomplished by establishing one station as the system clock.

(ABS)[45] provides an additional integrity monitor for the transmitted signal by blinking the Loran-C signal during out of tolerance conditions.[46] All these factors were considered in the evaluation team's analysis and modeling.

4.4.2 Propagation Hazards

Once the signal is transmitted, numerous propagation effects can degrade system performance by the time the signal reaches the user. The propagation effects are a major portion of the Loran system's error budget. These effects cannot be controlled but they can be monitored and, in some cases, compensated for in the receiver or transmitting equipment. The analyses identified and classified the hazards and often developed methods to mitigate the effects on the system's ability to meet the required performance parameters. The relevant hazards are described in the following subsections.

4.4.2.1 Spatial Variation of the Phase

As mentioned in Section 4.3.2, there are propagation biases in Loran that result in differences between absolute accuracy and repeatable accuracy. This is due to incorrectly predicted or incorrectly calibrated values for the signal propagation delays over land paths. A standardized method of specifying the phase delay has been established and officially promulgated [18]. The largest factor is called the "primary factor" and is needed for the initial position solution in a Loran-C receiver. In this factor, the propagation delay is directly related to the user's distance to the transmitter by a group velocity that depends on the index of refraction representative of the lower atmosphere. This fails to take into account the properties of the Earth's surface over which it is traveling. A "secondary factor" accounts for this lower waveguide boundary by modeling, with good fidelity, the delays encountered by a signal propagating over a seawater path. This is not linearly related to distance but can be calculated once an approximate path length is known. An "additional secondary factor" (ASF) accounts for additional delays of the Loran-C signal when traversing land paths. ASF can change rapidly from one user location to another as the terrain changes.

Typical ASF values in CONUS are in the 3 to 4 μsec range, although they can approach 10 μsec in extreme cases over long paths. The LORIPP performed an empirical analysis of available and practical ASF prediction models and concluded that, at the required levels of integrity, it could only bound ASF prediction errors at about 60 percent of the calculated ASF value. For an ASF just over 3 μsec, this corresponds to a 2 μsec prediction error, or 600 meters, which is outside the 556 meter HPL. The LORIPP concluded that while this accuracy level would be adequate for RNP 2 or even RNP 1, it would not meet the RNP 0.3 requirement. This means that ASF modeling alone is not a sufficient solution and that an actual ASF survey must be performed for each airport approach.

[45] ABS is a component of the Loran-C transmitting equipment suite. The purpose of ABS is to initiate "blink" without operator intervention when the transmitted Loran-C signal is outside an established tolerance.

[46] As discussed under receiver hazards and mentioned in the assumptions, procedure changes will be needed to have a station cease transmitting if an out-of-tolerance condition is detected.

The analysis also provided for a residual ASF error even after an airport survey. To model this error, the LORIPP commissioned an extensive computation effort using the best available propagation modeling technique [62]. The results show how rapidly the ASF can vary over an approach, and have been confirmed at several locations through data collection. The resulting predictions will need to be validated with flight tests during the approach calibration, but they can serve as an aid in planning the calibration effort. The results can also be used to give an indication of the expected calibration error. The LORIPP analyses determined that this component could be brought below 100 meters, as an absolute bound, with a single calibration point for a very large percentage of airports [63]. In the examination of sample airports exhibiting rapid ASF fluctuations, the team found that this 100-meter bound could be achieved with a few more calibration points. These values are used in the analysis model described in Section 4.6.

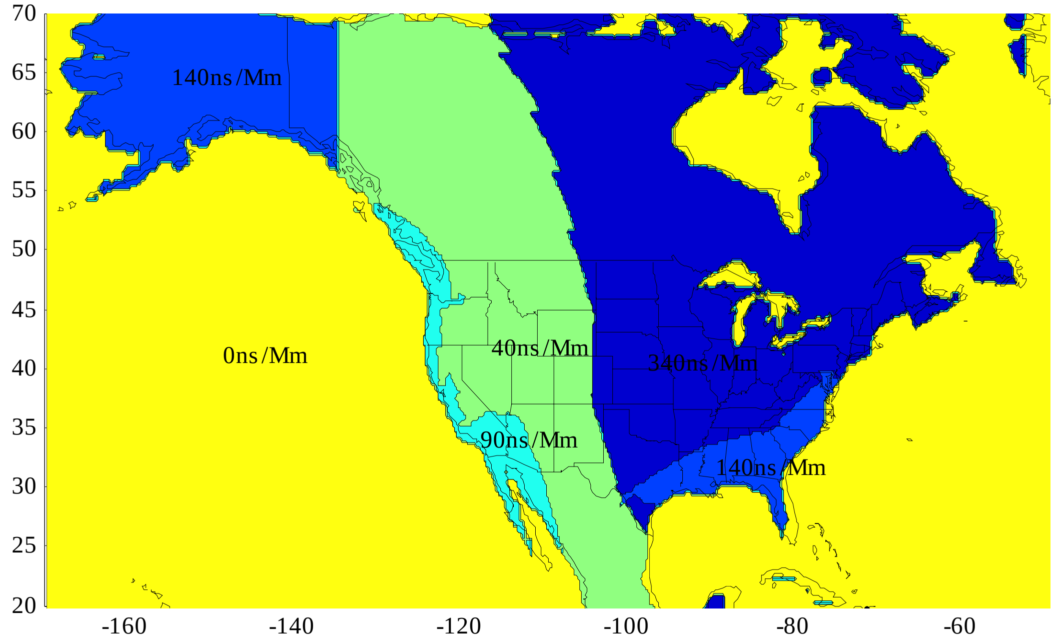
4.4.2.2 Temporal Variation of Phase

In the early 1980s, the U.S. Coast Guard (USCG) conducted a series of regional Loran-C signal stability studies that developed and empirically calibrated a model for explaining the seasonal variation in the signal propagation delays [64]. Temporal variations are much smaller than spatial variations but in extreme cases can exceed one μsec (300 meters) of error. The LORIPP identified two shortcomings in the results of the earlier USCG studies. The first shortcoming is that the studies did not encompass the entire CONUS.[47] The second shortcoming is that the model was not sufficiently developed to meet the LORIPP's needs. Specifically, the model was not viewed as having applicability at the required level of integrity and no effort was made to separate the variations into a correlated and uncorrelated bias term.

The LORIPP made two efforts to overcome these shortcomings. One involved the modeling of archived data from the USCG's network of monitor and transmitting station receivers. The second was the development of special data collection units to install at existing monitor stations to record data beyond that which the USCG currently archives. The stability study models were extended on the basis of these data collection efforts and the results were used in the performance models in Section 4.6 and Section 4.8. As in the earlier studies, the temporal variations vary in size from region to region (see Figure 4.4-1). The variations are largest in the northeast United States and Great Lakes, milder in the southeast United States, even milder along the west coast, and virtually non-existent in the high-altitude / low-atmospheric density of the western states.

[47] The program was terminated before the mid-continent stations were added and was not extended to Alaska.

Figure 4.4-1. Temporal Variation Regions for the United States



4.4.2.3 Spatial Variation of ECD

Knowledge of the expected ECD at any location is required for the cycle selection portion of the integrity calculation. It is well known that ECD also varies from location to location in the coverage area. The LORIPP confirmed that, as with ASF, there are no prediction models with sufficient fidelity at the integrity levels needed to support RNP 0.3 operations. Accordingly, ECD measurements are planned as part of the airport and harbor calibration efforts. The same high-density propagation prediction program that generated ASF variation maps was used to generate ECD variation maps [62], [65]. These programs were used to calculate the ECD errors that are expected to result from airport calibrations. The results are included in the performance model.

4.4.2.4 Temporal Variation of ECD

Studies from the early 1970s indicated that temporal ECD variations are slightly smaller than, but highly correlated with, temporal ASF variations. Accordingly, an early LORIPP effort examined archived USCG ECD records and confirmed that temporal variations could be modeled in the same way as the ASF variations. The LORIPP extended the examination of the USCG monitor data to calibrate the correlated and uncorrelated components of the variation, and the results are used in the performance model. As with ASF, the parameters of the ECD error model vary regionally.

4.4.2.5 Temporal Variation of SNR

An examination of the extensive data contained in the USCG archives confirmed that, at a given location, the signal strength of the received ground wave signal remains steady to within a fraction of a dB. This is well within the uncertainty of the signal strength predictions. Accordingly, SNR variations are determined by variations in the amounts of noise, discussed in Section 4.4.3.

4.4.2.6 Spatial Variation of SNR

The noise component of SNR is modeled as discussed in Section 4.4.3. The signal strength is modeled using Millington's method, which has been the Loran-C standard for decades [17]. The LORIPP compared predicted signal strengths with measurements taken at all the USCG monitor sites. In over 90 percent of the cases, the predictions matched the measurements or proved conservative by an average of 5 dB. Both the airport calibrations and the harbor surveys will afford an opportunity to refine these predictions. At present, it can be said that the predictions of coverage shown in this report are generally expected to be overly conservative by a few dB.

4.4.3 Receiver Hazards

Some of the hazards described in this section are definitely attributable to the receivers. Others, such as noise and interference, originate from external sources with effects that propagate to the receiver. Even so, they are best categorized in this section because the result of the effect is largely determined by the design of the receiving system, including the antenna.

4.4.3.1 Platform Dynamics

Because Loran-C signals are transmitted repeatedly at known intervals, receivers can achieve significant increases in effective received power by coherently averaging many pulses.[48] This reduces the effect of many sources of noise. In the face of noise, however, there are practical limits that depend on aircraft speed and acceleration. The LORIPP has analyzed the effects of platform dynamics on averaging and performance [66]. The analysis used the guidelines outlined in the WAAS MOPS concerning the limits of non-acrobatic aircraft performance with a maximum speed of 800 knots and a maximum acceleration of 2 g's (those obtained through 60-degree coordinated turns [67]).

4.4.3.2 Atmospheric Noise

In the low-frequency portion of the radio spectrum, considerable atmospheric noise can be present. This noise is generated by lightning throughout the world. It has been well established that a background noise level representing the sum of distant storms and bursts from more local storms can characterize such noise. The international standards body, International Radio Consultative Committee (CCIR), has produced an extensive

[48] These effects are seen in the ECD and phase estimates that determine the cycle selection and HPL/accuracy of the user and in the signal amplitude estimate that determines the time-to-alarm performance. Generally, it is a square law effect: quadruple the number of samples to cut the noise effects in half. However, the receiver platform (e.g., aircraft, ship) speed and acceleration limit how much averaging can be done. For example, if a receiver averages for 10 seconds, the resulting position would normally reflect where the platform was 5 seconds ago. This latency can be reduced in a receiver that makes, and uses, velocity estimates.

empirically based set of predictions of both these components.[49] The CCIR model is incorporated into the LORIPP performance model.

The LORIPP model also considers the effects of special receiver non-linear processing techniques that can detect, and virtually eliminate, the effects of the noise bursts. For the most part, the bursts are the reason the noise levels move above the 80 percent level. The model uses the term *clipping* to refer to a range of non-linear processing techniques that reduce these burst effects. On the basis of extensive studies of the literature and archived data, the LORIPP has concluded that it is conservative to claim only a 12 dB credit for clipping, and this is what is reflected in the performance model [68], [60].

4.4.3.3 Precipitation Static

Precipitation static (p-static) is noise caused by the discharge of charged particles that can build up on the skin of an aircraft as it passes through areas of adverse weather. Anecdotal information indicates this was a significant source of reduced availability when Loran-C NPA certification was being sought in the late 1980s and early 1990s [69]. The phenomenon can be greatly reduced through the installation of static dischargers and with good airframe maintenance. P-static was eliminated in military Loran-C and Omega receivers and in commercial Omega receivers through the use of single- or crossed-loop antennas—also known as H-field antennas [70]. Military standards exist for testing for p-static effects and were used in this project in aircraft charging tests (with all dischargers removed) [57], [58]. Test results showed that H-field antennas significantly reduce the noise effects.[50] The performance model uses a 40 dB above 1 microvolt per meter noise component to emulate the effect because tests show this is a very conservative bound. Additional tests to revalidate the prior tests are under way at the FAA's William J. Hughes Test Center and at Ohio University. The results of these tests, to date, are found in Appendix C.

4.4.3.4 Skywaves

The effects of skywaves can be mitigated in two ways. Long-delayed skywaves are "cancelled" by the Loran-C phase code once a receiver averages over a "phase code interval" (PCI)[51] of 16 pulses. To reduce early skywave effects, receivers can take advantage of the fact that skywaves traverse a longer path and will arrive later than the groundwave. Thus, if receivers use only the very early portion of the received signal, they are generally immune from this effect. Tests show that modern receivers, such as the USCG monitor receivers, easily exceed the protection specifications of both the past RTCA, Inc., and RTCM minimum performance standards for this characteristic [55], [56].

49 The effects of lightning will vary throughout the day and from season to season, so the CCIR model describes the effects for six periods of the day and four seasons of the year. Thus, for a given geographical area, CCIR would provide, for each of the 24 time periods, methods to compute the values not exceeded 50 percent of the time, 90 percent of the time, 99 percent of the time, 99.9 percent of the time, etc.

50 Results from tests conducted by Illgen Simulation Technologies, Inc. (ISTI) for the FAA, documented in the ISTI 99-R-217 report of April 1999, indicate that the H-field antenna is effective at mitigating the effects of p-static.

51 A PCI is equal to 2 GRIs.

However, the LORIPP, driven by the need to achieve the aviation integrity requirement, had to look more closely at this "hazard" and found that under conditions of adverse "solar weather," the ionosphere can be disturbed enough to create problems for signals traveling over long paths at northern latitudes [71], [72]. These problems occur when the disturbed ionosphere causes the skywave to have shorter than normal delays (< 25 μsec) resulting in interference with the early portion of the groundwave. The LORIPP analyzed this phenomenon and found it to be rare but not negligible in the lower 48 states.[52] Receiver design improvements have been developed to mitigate the effect of skywaves, but LORIPP determined that these receiver improvements alone would not reduce the integrity hazard to an acceptable level [53]. However, the LORIPP determined that these effects arise over a long enough period of time and a wide enough geographical area that the existing USCG monitor system can detect their (skywave) occurrence [73]. Use of this information and transmission of it via the 9th pulse communications channel (discussed in Section 5) provides a warning that meets the integrity specifications. To represent alarms from the detection process, additional ECD and phase error components have been included in the performance model. The reduction in signal availability is incorporated into the performance model.

4.4.3.5 Cross-Rate Interference (CRI)

All Loran-C chains use the same spectrum and transmit at times that periodically conflict with one another. This means normal receiver frequency filters will "pass through" signals from neighboring chains whose time of arrival will cause them to occasionally overlap, and interfere with, signals from local stations. This is referred to as cross-rate interference and causes noise-like variations in signal measurements that affect alarm detection, cycle selection, and HPL calculations.[53] In the early 1990s, digital signal processing methods were developed that effectively eliminate the cross-rate interference effects [74]. These include cross-rate blanking and cross-rate canceling. Cross-rate blanking greatly reduces the number of usable pulses. As such, it is only appropriate for applications with low dynamics. Hence the performance model for RNP 0.3 analysis assumes vendors will employ cross-rate canceling, or some equally effective method, to eliminate cross-rate interference. A slight variation is that this technique will not be effective in eliminating the effect of the 9th pulse modulation described in Section 5, although it can be blanked, resulting in a slight loss in signal.

4.4.3.6 Man-Made Radio Frequency Interference (RFI)

Interference from man-made sources comprises continuous wave interference (CWI) [75] and power line carriers (PLC) [76], [77]. Both result from broadcasts that are in or near the Loran-C band. CWI effects have been greatly reduced in recent years in North America for three reasons. First, the Decca navigation system that shared the low-frequency (LF) frequency band was a major source of such interference and has been

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[52] For receivers south of 60^{o} geomagnetic north during a moderate period of the solar cycle, this phenomenon occurs 6 hours per year, resulting in a loss of availability of 7x 10^{-4}.

[53] Averaging, as discussed above, can reduce the effects, but is limited by platform dynamics. The Loran-C phase code will reduce some of the effects but, as described in the previous section, was primarily developed to eliminate the effects of long-delayed skywaves. As a consequence, even hour-long averages of cross-rate interference will not "zero out" this effect.

terminated. Second, Navy fleet broadcast at LF was greatly reduced at the end of the Cold War. Third, effective automatic notch filters using digital signal processing techniques are available. The LORIPP considers CWI to be a hazard that is too insignificant to model, assuming receiver performance specifications properly address the potential hazard.

PLC effects arise when the power transmission system uses the navigation frequency band for power grid control messages because the operators do not think they are interfering with anyone. Such instances have been virtually eliminated in most parts of the United States but will have to be considered during both airport and HEA calibration efforts.

In addition to unintentional sources of interference, the possibility exists of deliberate interference in the form of jamming or spoofing. However, the possibility of these events is extremely remote. The LORIPP has examined and modeled these interference sources and concluded that they are not a source of concern (see Appendix C and Reference [78]).

Avionics and other aircraft equipment such as motors and generators emit electromagnetic noise that can interfere with the incoming Loran-C signal. Aircraft noise varies with aircraft type, configuration, installed equipment and type, and location of the Loran-C antenna. Decades of successful operations by military and commercial Omega and Loran-C receivers have demonstrated that these problems can be overcome by adequate installation procedures [70], [79], [80].

4.4.3.7 Structures

Re-radiation of the Loran signal can occur off large (at least several hundred meters) ungrounded metallic structures, such as the spans of suspension bridges. These are unlikely to exist in the vicinity of airport approaches, but calibration efforts will have to include the possibility in the list of effects to look for. They are very likely over several major waterways, though the bridges are typically not in the most restricted reaches of the waterways. These effects are not included in the general performance model because they are specific local effects. They must be handled, as necessary, in aviation and HEA calibration efforts on a case-by-case basis.

4.4.3.8 Receiver Calibration

Historically, an improperly calibrated receiver has produced hazards for two parameters—phase and ECD. The largest part of the phase offsets is common from one signal to another and only affects the timing estimate—not the navigation or frequency estimates. Second- and third-order effects on the phase result because signals being received over different propagation paths have different degrees of distortion and the receiver responds to each differently. Such effects are incorporated in the performance model.

The ECD estimates are inherently more sensitive measurements because the effective SNR is about 50 times less than for the phase. More important, older receiver models made individual cycle selections for each signal. Receiver calibration effects are greatly reduced when the over-determined solution discussed in Reference [59] is used, as is currently deemed necessary. An additional method is to “calibrate” the receiver ECD estimates based on the strongest received signal. Both these methods eliminate common errors that will be the largest receiver calibration error component. Residual ECD receiver calibration errors are included in the performance model.

4.5 CUMULATIVE HAZARD ANALYSIS

Section 4.4 described the individual hazards that were identified and addressed for this report. The LORIPP conducted a cumulative hazard analysis in the development and review of the overall performance prediction model that is described in the next section. Accordingly, it is useful to present an overview of the hazard diagram and how it is used. As mentioned earlier, the performance model can actually be thought of as primarily examining integrity and then determining the resultant availability and continuity. Accordingly, there is an integrity hazard diagram. As also mentioned, there is no need to examine accuracy once integrity is considered. Availability can be calculated by applying the resultant integrity bound and tabulating the percentage of the time that the bound is below the alarm threshold. Although continuity is strongly related to availability, the fact that it is a conditional probability of interruptions over short durations creates enough change in the treatment of the hazards that a short hazard analysis is helpful. Integrity and continuity hazard analyses are discussed in detail in Reference [81]. This section provides a brief overview of the integrity cumulative hazard analysis.

Figure 4.5-1 shows a high-level view of all the elements of the integrity hazard diagram. Figure 4.5-2 shows the expanded view of the cycle integrity branch of the full diagram. The discussion will focus on the latter component to illustrate the analysis method. Starting at the left, and at the bottom, the diagram shows that spatial and temporal ASF components contribute to the overall ASF hazard. Specific values for the statistics are considered in sensitivity analyses. For example, the sensitivity of various airport spatial ASF calibration methods/accuracy specifications has been analyzed relative to overall cycle integrity. The diagram illustrates how the ECD hazard is similarly affected by a spatial and temporal component but also by the effects of early skywaves, which are most severe in the ECD estimates. After the ASF and ECD errors are known for each signal, the specified noise level is used, in conjunction with computed signal strengths, to define all the components necessary to compute the probability of an initial cycle integrity failure. This completes the left path of the hazard diagram in Figure 4.5-2.

Figure 4.5-1. Full Integrity Hazard Diagram

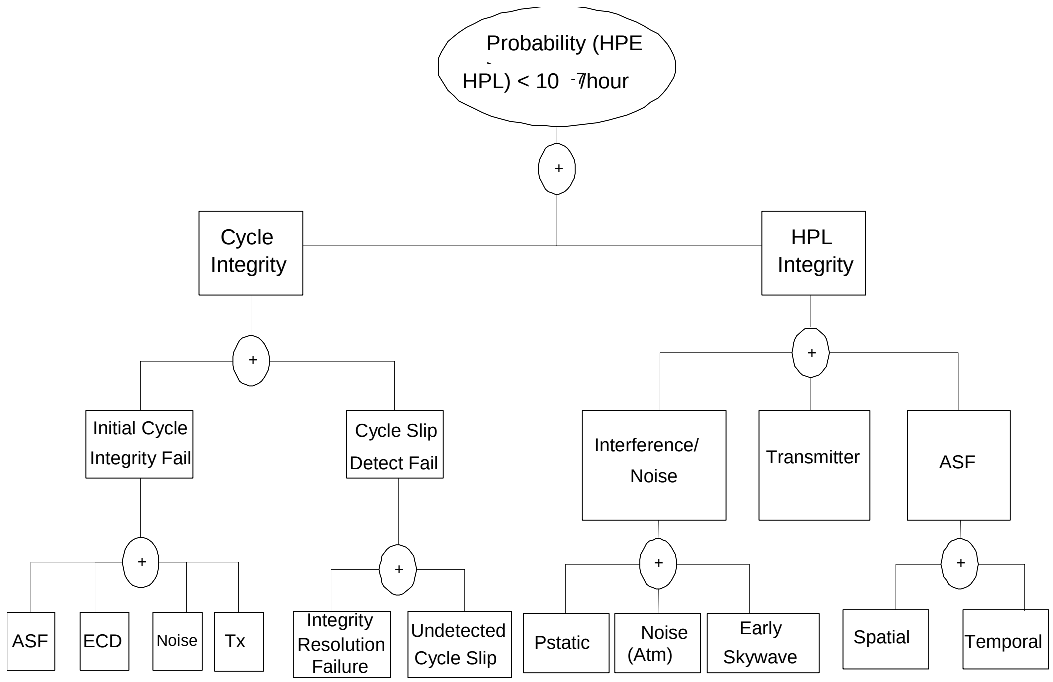
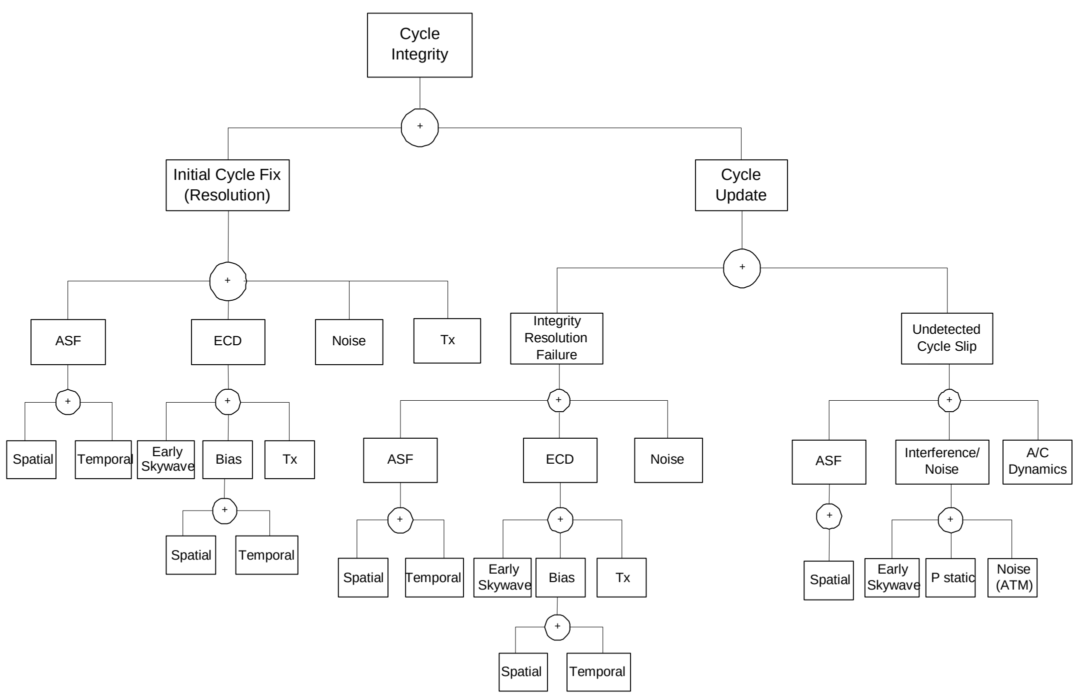


Figure 4.5-2. Expanded View of Cycle Integrity Side of Integrity Hazard Diagram



In the second path, the hazard considered is a cycle slip detector failure. The left path called “integrity resolution fail” is identical to the initial cycle selection failure calculation, indicating that a receiver will continually and periodically attempt to re-validate the initial cycle selection. This path of the cycle-slip detect branch involves computations for an undetected cycle slip. This calculation for the cycle slip detection does not involve ECD, and thus this source of uncertainty is eliminated from this portion of the hazard. The slip detection calculation is completed in less than 10 seconds, which is too short a period for there to be any noticeable temporal change in ASF. Accordingly, the only contribution to the ASF calculation is the small amount of spatial ASF change that can occur over the distance an aircraft can travel in 10 seconds. The LORIPP has determined that this can be bounded at 0.4 µsec (see Appendix C).

The LORIPP chose to apply the model for an aircraft at the maximum specified speed making the most rapid turn while heading toward a station being received at -10 dB SNR. On all accounts, this will bound the problem. A receiver could possibly be designed to increase its signal tracking performance by considering the specific SNRs, bearings to the stations, and measurements of the current aircraft dynamics. The LORIPP uses the calculations previously discussed, along with calculations for the HPL branch of the integrity hazard diagram, in implementing the performance model.

4.6 AVIATION RNP PERFORMANCE MODEL

As mentioned earlier, the LORIPP’s RNP model evolved from an iterative application of many of the elements introduced in the preceding section. For example, the LORIPP had an initial performance model that assumed the spatial ASF hazard could be adequately handled by ASF predictions. The expected performance was analyzed using prediction methods. This analysis created spatial ASF error components that could be assessed by applying an early version of the performance model. The model results show that RNP 0.3 requirements could not be met in most of CONUS. This finding led to several actions. The need for a local ASF calibration at each airport was added to the list of assumptions in Section 4.2, and an analysis was undertaken to determine a reasonable model of the spatial ASF error after such a calibration. When detailed modeling and analyses indicated that the 100-meter bound was feasible and practical, it was incorporated into a revised performance model that showed RNP 0.3 was achievable almost everywhere (see Appendix C, [63], [36], and [82]).

Similarly, as other hazards were examined, their effects on overall performance were assessed and target levels were established; these levels are conservative estimates so that the results are of the model will also be conservative. As appropriate, the effects, or the hazards themselves, were added to the hazard diagram. The net result is the model in its current form. The model is best described by walking through the sequence of execution. It should be noted that for all the calculations described herein, the potential coverage area was divided into cells that are about 30-km square. Calculations were made for each such cell.

4.6.1 Initial Signal Selection

The analysis begins by establishing the noise percentile level. For many scenarios analyzed, a typical starting level would be 99.5 percent. For a full analysis to enable availability tabulation, a series of tests at various noise levels is undertaken.

These analyses have shown that the 10-second time-to-alarm component of the integrity requirements can be met—but barely—in the face of expected aircraft dynamics, at SNRs down to -10 dB, if the alarm mechanism is transmitter blink.[54] If the alarm mechanism is changed to off-air, the required detection time is substantially reduced. Besides allowing for a slight safety margin, a 3-second momentary off-air can be discounted and a real off-air can still be detected within the allotted time. Accordingly, a requirement has been established that the only signals to be used in calculating positions are stations with an SNR of at least -10 dB. Therefore, at the conclusion of this step, the model has a list of stations to consider in subsequent steps. Depending on the location and noise level, six to eight stations generally are used.

4.6.2 Initial Cycle Selection

Analysis indicates that there is a maximum allowable amount of signal averaging for ECD and phase measurements, at expected aircraft speeds and accelerations. Although much more averaging can take place if the initial acquisition occurs before takeoff, problems that require that the initial acquisition take place in flight must be included. The maximum ECD averaging time establishes the minimum SNR at which the correct cycle for a single station can be determined within the integrity limits. If the received ECD at a given location is perfectly known, this would be 0 dB SNR. With the levels of uncertainty modeled for the various ECD hazards, however, this minimum SNR becomes about +4 dB.

A substantial portion of the desired coverage area usually has three signals with at least +4 dB SNR available. If this is the case, a high-confidence position can be established and used to determine the correct cycle for weaker signals. However, the LORIPP analysis also shows that there remains a non-trivial percentage of the desired coverage area that does not receive three stations at an SNR above +4 dB at the noise levels required. For this purpose, the LORIPP model employs a method that is described in References [59] and [83] that can be used when more than three stations are available, as is almost always the case. Depending on the various SNRs in the available set of stations, successful cycle resolution can be achieved for some stations down to -10 dB SNR. Without this method, RNP 0.3 coverage is limited. With this method, RNP 0.3 coverage is substantial.[55] Accordingly, this method of cycle selection was added to the list of assumptions that all users will apply.

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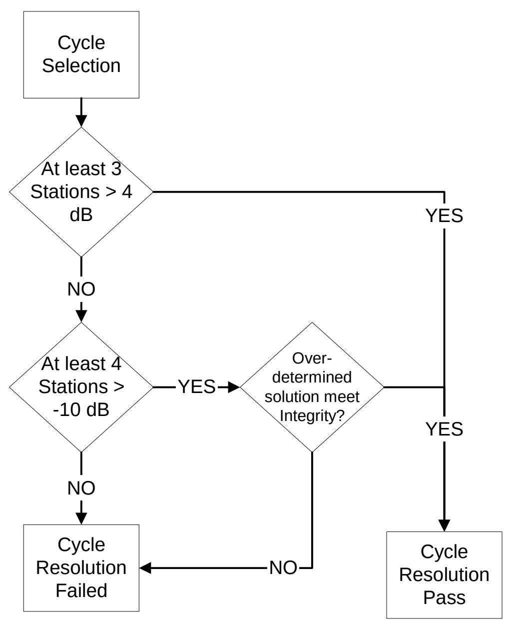
[54] Blink indicates that signal is unusable resulting in a change in the transmitted signal format as described in the Loran-C signal specification.

[55] If *N* stations meet the -10 dB SNR requirement, the model might find that a receiver could resolve the cycle selection problem for all *N* stations. Alternatively, this might not be possible for the weakest signal but could be for a set of *N*-1 stations. If *N*-1 is 3, the process ends. However, if *N*-1 is greater than 3, the model will determine if cycle selection can be achieved for any subsets of the *N*-1 signals. This is important to know because it will

4.6.3 Subsequent Cycle Resolution

As shown in the hazard diagram in Figure 4.5-2, after initial cycle resolution, the receiver continuously and periodically repeats the process (see Figure 4.6-1). Because of the required ECD averaging time, this would typically take about 30 seconds, though specific receiver implementations might extend this to once a minute. The process is identical to the initial cycle selection task described in Section 4.6.2. It is important that this process be periodically repeated as the user moves through the coverage area because some stations must be released and new, previously weak stations may "come into view."[56] It is worth mentioning that if a receiver is already operating with integrity when a new station goes above the -10 dB threshold, that receiver will know where it is within 556 meters and know the expected time of arrival of the new station to within 1 to 2 µsec (better than 600 m). Thus, the requirement to determine the correct time of arrival within ±1500 meters can be easily met. However, the model includes the mechanism to periodically "start from scratch" to be conservative.

Figure 4.6-1. Cycle Selection Flow Chart



The hazard diagram also indicates a cycle-slip detector. However, it is highly unlikely that a receiver would ever "slip cycle" after it has successfully begun tracking a station.[57]

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determine what degree of redundancy, if any, is available at the location. More often than not there is redundancy and this improves the availability and continuity parameters. At the conclusion of this step, therefore, the model has a list, for each cell in the potential coverage area, of the signal combinations for which initial cycle selection can be expected above the seven 9s confidence level, as well as the expected specific confidence.

[56] The stations' SNR is at a level to be received and used by the receiver.

[57] Even so, a high-quality slip detector can be employed to ensure that this eventuality would not lead to hazardously misleading information with probabilities well above the requirement. The basic process is to work off the notion that if the cycle selection is known to be correct at time *t*, simple calculations can show that the chance of being on the wrong cycle (for each station) is small at time ($t + x$), as long as x is not too large. Specifically, for an aircraft executing a 60-degree turn at 600 knots, if x is 8 seconds, the maximum error in our ability to predict from t to

Currently, slip detector calculations are not made in the performance model because the probability of no "cycle-slip" condition is nearly one. Thus, as presented in Appendix C, the slip detector does not have to be included in the model. The LORIPP acknowledged the phenomenon in the integrity hazard diagram and plans to require slip detectors in receiver specifications. However, the hazard analysis shows that the probabilities of a slip are so small that the outputs from this process are unchanged from the step described in Section 4.6.2.

4.6.4 HPL Calculation

This is the second branch of the full integrity hazard diagram (see Figure 4.5-1) and is performed for all sets of stations for which the cycle selection can be completed at the desired level of confidence. At this stage, ECD is no longer a factor. Instead, the concern is the phase errors for all signals involved in the set of signals being studied.

The calculation proceeds by computing the cumulative effect of all the hazards affecting each station, sorted by the type of error component—random, correlated bias, and uncorrelated bias. As indicated earlier, the spatial ASF error is a main source of uncorrelated bias error. Because the spatial component results from a government calibration, a bound is provided, for each approach, at the same time the calibrated ASFs and ECDs are published. The temporal ASF errors, which are divided into correlated and uncorrelated biases, are also provided by the government in the form of an algorithm that depends on the signal path length and the region in which the signal path lies. Transmitter noise will comprise both a random and an uncorrelated bias error and also will be provided by the government (e.g., via the tolerances listed in the signal specification).

Early skywave is a problem that the LORIPP has concluded cannot be detected by a user receiver with sufficient integrity (References [72] and [73]). Accordingly, a monitoring program that will detect various levels of the effects (as a function of path length and latitude) must be established to broadcast warnings via the 9th pulse communications channel described in Section 5. This communications channel will be designed to ensure the early skywave is *not* a threat to integrity, but it does have a limiting effect on availability. In the LORIPP model, the effect is addressed by limiting the stated availability of signals at long ranges.[58] The remaining factor that affects the phase accuracy is the total random noise. For a receiver, this is a simple calculation, that is, it computes the standard deviation of the phase samples for each signal being used. The LORIPP model predicts the signal strength and the noise effects, as described in Section 4.4.2. The result of this prediction, for a given noise level, is an assessment of whether or

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($t + x$) due to aircraft dynamics is about 2 μsec. This leaves us ±1.5 μsec additional error due to noise-induced error in our position estimates at times t and ($t + x$). With our phase averaging times, this 1.5 μsec threshold would not be exceeded by a -10 dB SNR signal at the "nine sigma" level. This means we can repeatedly use the slip detector for days and still have a negligible chance of slipping cycle.

[58] For the Alaska paths, the effect is most pronounced and reduces the single baseline availability, depending on the path length, into the range from 95 percent to 99 percent. In the conterminous United States, the effects are modeled by reducing the availability of paths over 800 km by a factor of 0.9993.

not the desired HPL is achieved in each cell. If it is, the associated RNP level is provided in that cell at that noise level and, therefore, the system is available at that level.

4.6.5 Availability Calculation

After the presence or absence of integrity is determined for each cell and for each noise level, the model can combine this information with the signal availability information to compute a composite system availability number for each cell. The availability statistics come from a station availability model, as modified by early skywave factors that depend on path length and latitude.

4.6.6 Continuity Calculation

Continuity is defined as one minus the probability that a service will be interrupted during a specified operation. For aviation purposes, the operation is a 150-second non-precision approach. Assuming that the correct cycle is known at the start of the specified operation, the continuity calculation determines the probability that it would be lost in the next 150 seconds. This equals about a 20-cycle-slip calculation period. As indicated earlier, the slip detector can have such a high success rate that the probability of the user receiver not making 20 consecutive successful slip detections is negligible. So, too, is the probability that the user receiver would actually slip a cycle. Thus, the entire cycle selection path of the integrity hazard analysis is eliminated for continuity purposes.

The major remaining question involves the probability of loss of a critical transmitter during the approach. This situation depends on the set of stations available. If no station is critical, the calculation is reduced to the chance that two stations go off-air simultaneously (given that they were on air at the start of the approach). This calculation is straightforward. Other remaining questions involve the probability that events such as high noise, early skywave incidents, or p-static will occur over a 150-second period. The evaluation team's model can estimate these event probabilities and calculate the continuity. Currently, these incidents are expected to affect less than 0.1 percent of the time and are not incorporated because this is below our calculation threshold.

4.7 AVIATION RNP MODEL RESULTS

Sample figures provided in the early sections of this report give an indication of the output of the performance model. What follow are additional coverage plots and associated discussions to further demonstrate Loran-C's capability to meet the new modal requirements. The key for the coverage diagrams is presented in Table 4.7-1. A discussions of these parameters in contained in Appendix C. The parameters for the coverage diagrams in this section are not changed unless noted.

Table 4.7-1. Key to Terms Used to Describe the RNP Coverage Plots

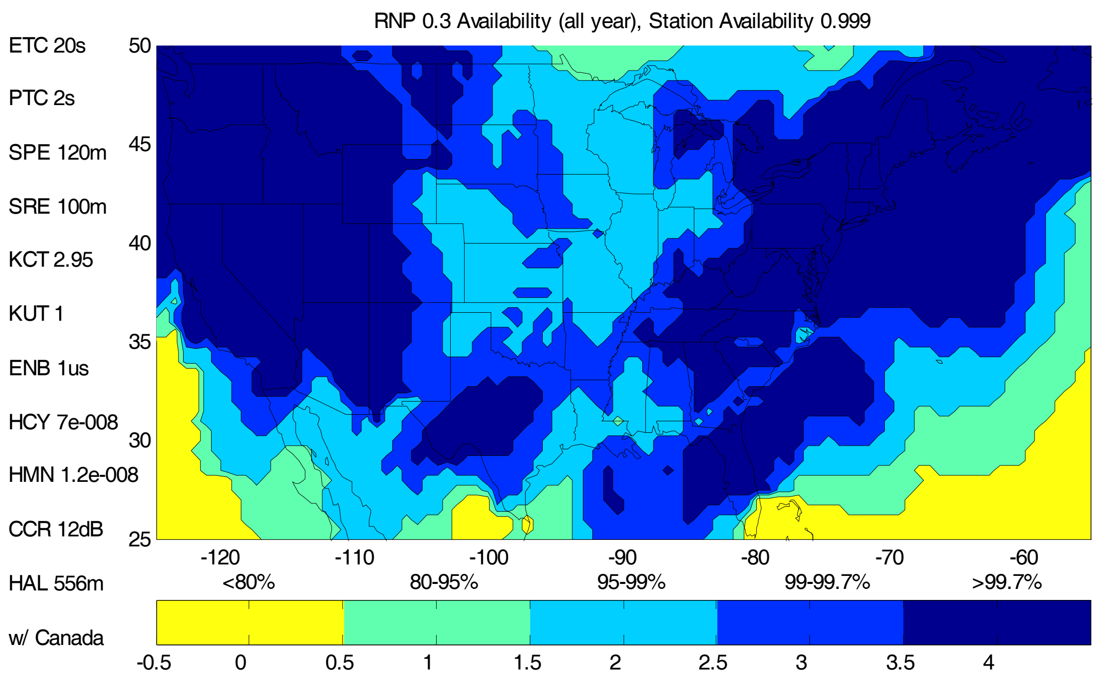
Item	Model Parameter
W/O	With or without Canadian stations
HAL	Horizontal alarm limit
CCR	Credit for clipping

Item	Model Parameter
ENB	ECD bias
ETC	Seconds to average envelope
PTC	Seconds to average phase
ASF	Decorrelation in cycle integrity
SPE	Range error for spatial
SRE	Position error for spatial ASF decorrelation in HPL
KCT	Coefficient that scales correlated seasonal phase variation map
KUT	Coefficient that scales uncorrelated seasonal phase variation map
HMN	Threshold of probability for Gaussian noise contribution to HPL
HCY	Threshold of probability of undetected cycle error

4.7.1 RNP Coverage

Figure 4.7-1 illustrates the expected coverage of the modernized Loran system in the conterminous United States based on the current aviation RNP.03 requirements. This figure shows the various availability levels for the required integrity and accuracy.

Figure 4.7-1. Expected RNP 0.3 Modernized Loran Coverage (Availability Contours in Percent) in the Conterminous United States with the Existing Infrastructure[59]



[59] Infrastructure includes the Canadian stations.

Figure 4.7-2 shows continuity levels for the required integrity and accuracy. Detailed comparisons confirm what a visual examination suggests: Wherever there is availability at a certain level, there is continuity at the same, or a higher level.

Figure 4.7-2. Expected RNP 0.3 Modernized Loran Coverage (Continuity Contours in Percent at a 0.999 Station Availability) in the Conterminous United States with the Existing Infrastructure[60]

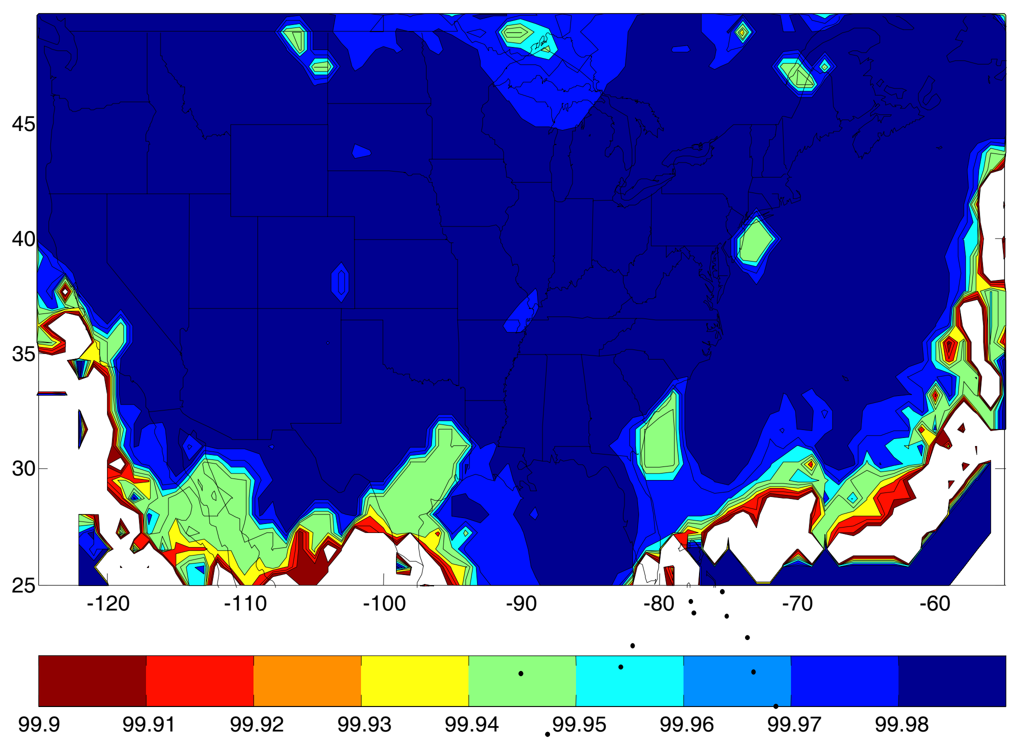
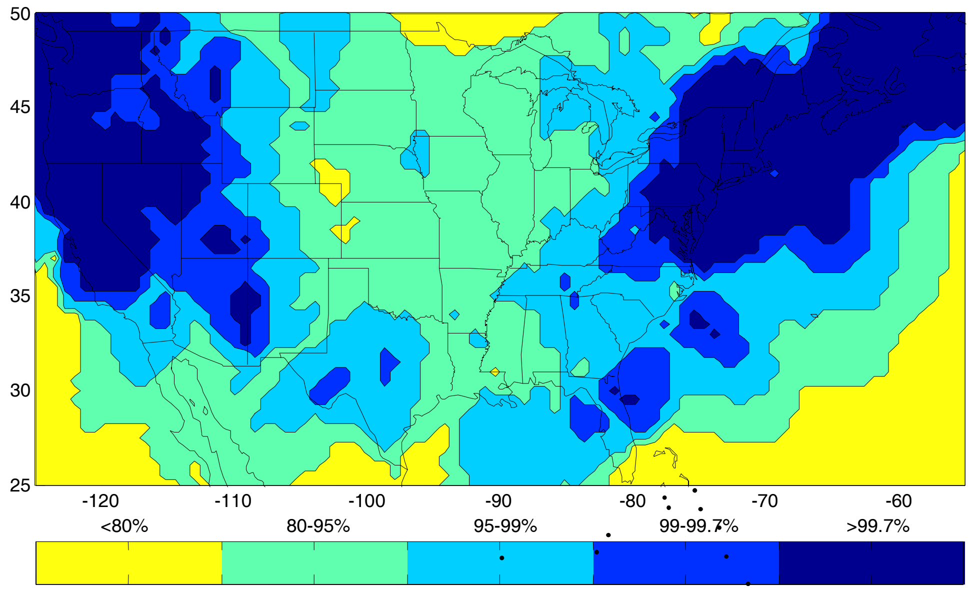


Figure 4.7-3 illustrates the expected coverage if the time block with the worst level of atmospheric noise is used at each location. This time period is usually summer afternoon. The results show diminished availability, particularly in the center of the country. The results depicted are due to the conservative nature of the noise estimate in the model. However, the worst-case noise values have significant uncertainty associated with them. Data taken have suggested that the extreme worst case noise values are not as large as those used for this figure, hence these results are overly pessimistic. The team is certain that the coverage under these worst-case conditions will not be less than what is presented in this figure. Additional investigation is currently being conducted. This topic is further discussed in Appendix C.

60 Infrastructure includes the Canadian stations; all model factors are unchanged from Figure 4.7-1.

Figure 4.7-3. Expected RNP 0.3 Modernized Loran Coverage (Availability Contours in Percent) in the Conterminous United States with the Existing Infrastructure for the Worst Noise Time Block at Each Location. [61]



4.7.2 Acceptance in RNP Applications

One of the most important issues concerning modernized Loran system aviation usage is the user's operational need for an independent RNP 0.3 RNAV capability. This is an individual user decision based on the user's tolerance level for operational effects of GPS outages. However, user acceptance also requires a government commitment to provide the service for a viable commercial market to be generated [20]. The combination receiver (GPS/modernized Loran) or stand-alone Loran-C receiver does have the benefit of being able to support operations, including NPA- and RNP-based departure procedures, during a GPS outage. In this case (RNP 0.3 or enroute), the navigation capability could seamlessly change from GPS to Loran and allow for continued operation. Other factors necessary for aviation acceptance are as follows:

- Updating the established monitor sites
- Finalizing the Loran data channel modulation method
- Developing certification standards for aircraft avionics.

4.8 MARITIME HEA PERFORMANCE MODEL

This section addresses Loran-C's performance as it applies to maritime applications and other applications that may have similar requirements. Up to this point, aviation requirements have been the primary focus. Fortunately, most of the assumptions and

[61] Infrastructure includes the Canadian stations; all model factors used for Figure 4.7-1are the same except for noise.

elements of the aviation RNP performance model, in some form, can be used by the maritime HEA model. The HEA model can be understood by discussing how it differs from the RNP model. These differences include the requirement for real-time differential corrections for ASF and modeling their effects, the requirement for an extensive track-line survey, and elimination of the cycle-selection integrity hazard. As with the model, and similarly to the aviation tests, the evaluation team demonstrated actual performance by conducting on-air tests. These tests used an imbedded correction on the modernized Loran signal (much like differential GPS [DGPS] corrections)[62] to prove that Loran-C can meet the level of accuracy required in the HEA environs. Thus, a modernized Loran can be considered as a potential alternative system with respect to maritime navigation and port operations when GPS is unusable. The communication method is discussed in further detail in Section 5.

4.8.1 Differential Corrections Requirement

Accuracy is the major factor affecting the suitability of Loran-C for maritime navigation and associated applications. Loran-C's current accuracy of 0.25 nm for open ocean navigation is in accord with current International Maritime Organization (IMO) navigation practices. However, IMO and USCG standards for the region of harbor entrance and harbor transits specify a more stringent accuracy requirement of 8 to 20 meters (95 percent of the time). The HEA accuracy requirement is a significant challenge that was overcome by using differential corrections.

The current bound for the HEA requirement is for an accuracy of 20 meters and an HPL equivalent parameter at the 50-meter level. As developed in Section 4.8.3, cycle selection, which is still necessary, is essentially eliminated as a hazard by using differential Loran-C corrections. Thus, the phase path of the integrity hazard diagram is the dominant concern. HEA requirements effectively increase the integrity to an accuracy ratio of RNP 0.3 from 1.8 to 2.5. Because the allowable probability of integrity failure for HEA is $3x10^{-5}$, the extreme tails of the distribution are not as significant as with RNP. Thus, the calculation of integrity and accuracy are much more closely aligned for HEA. These two factors led the LORAPP to conclude that if HEA accuracy can be achieved, HEA integrity can be achieved. Numerous past studies, dating from the early 1970s to the mid-1980s, had examined differential Loran-C and indicated that such accuracies were within reach [16], [51], [52], [84].

To achieve accuracies on the order of 20 meters, spatial errors must be nearly eliminated. This is achieved by the track-line surveys described in Section 4.8.2. This leaves the temporal signal phase variations, which are modeled with the same parameters used for RNP analysis. Depending on the region of the signal path, the correlated term will be specified as a stated number of nsec (1-sigma) per 1,000 km. This follows directly from the 1980s stability studies [36],[37], [38] updated by additional data modeling by LORIPP and LORAPP. There will also be an uncorrelated term, stated as a bound in nanoseconds, which will vary per region.

[62] Similar to the DGPS correction; however, unlike DGPS, it is not transmitted on a separate frequency.

The major difference is that the paths to which these parameters are applied are not the same. For RNP calculations, the path of interest, for each signal, is from the transmitting station to the user. However, for differential Loran-C, the path is actually a path pair calculated as the length of the path from the transmitter to the user minus the length of the path from the transmitter to the differential monitor. If the user is virtually collocated with the monitor, this term vanishes. Even if the user moves away from the monitor, this term remains small if the movement is along a circular path with the circle centered at the transmitter. An error that actually occurs with distance from the monitor station is, according to the model, uncorrelated from signal to signal. The specific value is taken to be consistent with the uncorrelated component used in the RNP analysis over the average path length modeled in that region (worst case).

The previous discussion describes only the functional difference between the RNP and the differential Loran-C models for the protection level. An additional error term is a random component that depends on the SNR of each signal. This component is calculated in the same manner as in the RNP analysis except that a longer marine time constant is assumed. The final term is also analogous to an RNP approach model term and involves components that are independent of position such as transmitter noise, base station noise, and grid accuracy and modeled as uncorrelated from station to station.

4.8.2 Track-Line Survey Requirements

If Loran-C is to be a radionavigation input in maritime applications, the user will need almost the same performance as the primary system (GPS).[63] Because accuracy is the key performance requirement, an extremely detailed knowledge of a port's seasonal and spatial ASF is needed. This, in turn, requires—

- A spatial survey of the port
- A monitor network in the port
- A modulation method to transmit the differential corrections
- An integrated navigation receiver (i.e., GPS and modernized Loran).

Given a harbor area has a requirement for more than 10 times the accuracy of a non-precision approach, there is a requirement for many more calibration points per unit area.[64] Calibration points every 100 meters are typically considered more than adequate [84]. With a properly instrumented data collection set, considerably smaller data sample spacing can be expected. Thus, post-data collection analyses can confirm that calibration errors are small enough to meet requirements.

[63] The importance of radio navigation systems has grown with the acceptance of real-time charting displays. Many vessels no longer use paper charts and use only electronic charting displays minimizing the personnel on the bridge required for navigation. As electronic charting becomes more standard, the skills of paper charting will be forgotten, furthering the absolute need for a radionavigation system to provide input for the electronic charting.

[64] This fact was demonstrated by USCG R&D efforts in the late 1970s and led to the development of track line survey techniques. Back then, the demands were much more difficult because neither GPS nor its augmentations were available and various high-accuracy reference systems had to be specifically deployed. By contrast, with DGPS and WAAS now widely available, high-quality reference information can be much more readily obtained.

The second bullet above specifies the establishment of at least one, possibly more, fixed reference stations in the calibration area. These stations will collect data throughout the calibration period and enable the effects of temporal grid variations to be reduced to the desired level. Techniques for these analyses were developed in the early 1980s [36], but need to be improved in view of the more capable position-reference systems currently available. As noted in the previous section, an estimate of expected imperfections in the grid calibration is included in the model that predicts modernized Loran's performance.

4.8.3 Elimination of Cycle Selection Integrity Hazard

Accuracy was the greatest challenge to Loran-C HEA requirements. The phase accuracy had to be reduced by a factor of approximately 10 to 15 from the RNP 0.3 requirements, which prompted the need for the mitigations mentioned in Section 4.4.2 to greatly reduce the magnitude of temporal and spatial phase error components. However, the cycle selection demands are no different for HEA and RNP 0.3. This is of benefit for several reasons.

First, vessel dynamics are different in the maritime environment, enabling the averaging time for the envelope to be at least four times longer. This factor results in a +6 dB improvement so that individual station cycle selection may be completed at SNRs down to about -2 dB. In the potential coverage area, there will always be at least one and almost always two or more stations above this level. The need to rely on the over-determined solution approach to cycle selection, therefore, is greatly reduced. At the same time the standard deviation of the ECD estimate, a major factor in limiting success in the over-determined approach, is reduced by half. Moreover, ASF errors are important to the success of the over-determined solution approach. For all practical purposes, these errors are eliminated in the HEA environment because of the track-line survey and differential corrections. The result of both effects, and what the analysis shows, is that a cycle selection failure in the HEA environment is never expected.

4.8.4 HEA Test Bed

The magnitude of the development effort and time available drove the evaluation team to quickly develop a modernized Loran test bed to demonstrate modernized Loran's capabilities in the HEA environment. The evaluation team established a test bed using 1980s USCG differential Loran-C work as a foundation. The process included the following steps:

1. Development of a process to survey waterways and conduct a survey for spatial ASF.[65]

2. Design and installation of a maritime differential monitor system in a specific area.[66]

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[65] The test area was the Upper Chesapeake Bay. A spatial grid was completed for this area for a differential Loran-C system. The USCG partnered with the U.S. Army Corps of Engineers, using the motor vessel (M/V) *Shuman* to complete this spatial grid on some areas of the waterway in the test area.

[66] The demanding, detailed nature of the surveys, as well as the specifics of the proposed communication method,

3. Calibration of the spatial grid using a land-based monitor for temporal corrections.
4. Development of a means to transmit the spatial corrections via Loran modulation.[67]
5. Collection of data from the test bed to validate the HEA model's predictions with empirical data.
6. Development of an all-in-view modernized Loran receiver to produce a differential Loran navigation solution.

The result of this process was a test bed for an improved differential Loran-C system consisting of monitor sites to collect correction data, spatial grids to establish a baseline reference, all-in-view maritime receivers that demodulate and apply differential corrections, and equipment for the transmission of the differential corrections.[68] The test bed began operations in November 2003. The tests[69] focused on using one site as the base-station provider of differential corrections to correct the position accuracy at other locations.[70]

Figure 4.8-1 shows the cumulative distribution of modernized Loran position errors using DGPS as the reference.[71] The result is an accuracy of approximately 25 meters (95 percent of the time) compared with DGPS. In this specific instance, the 20-meter "requirement" is not met. However, it could be that the 20 meters is not actually required at this location. If it is required, the situation could be improved by the addition of a monitor (Appendix C and Reference [49]).

The test-bed results were also used to develop a generic model for a port. Figure 4.8-2 shows the modeled performance of a hypothetical differential monitor network in the Upper Chesapeake Bay. These results indicate the realistic potential that modernized Loran system can meet HEA requirements. However, additional work is required before a differential system is fully operational (e.g., harbors surveyed and monitor sites established).

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limited the test bed to a port area where transmitters and monitors were available nearby for testing.

[67] See Section 5, Loran Modulation, for a more complete discussion.

[68] The test-bed comprised a monitor network (three sites) and transmitting site to cover the region between upper Chesapeake Bay and the Delaware River. The differential corrections were imbedded in the Loran-C signals broadcast from the test transmitter at the USCG Loran Support Unit in Wildwood, NJ.

[69] The evaluation team tested the complete system of monitor sites, spatial grids, and all-in-view maritime receivers that demodulate and apply differential corrections, as well as the on-air transmission of the differential corrections.

[70] The correction data were broadcast on the Loran-C signal using a pulse position modulation method. This method and other data channel research are detailed in Section 5, Loran Modulation.

[71] For the purposes of this test, DGPS is considered the receiver's actual position.

Figure 4.8-1. Cumulative Distribution of Position Error for November 2003 Trials

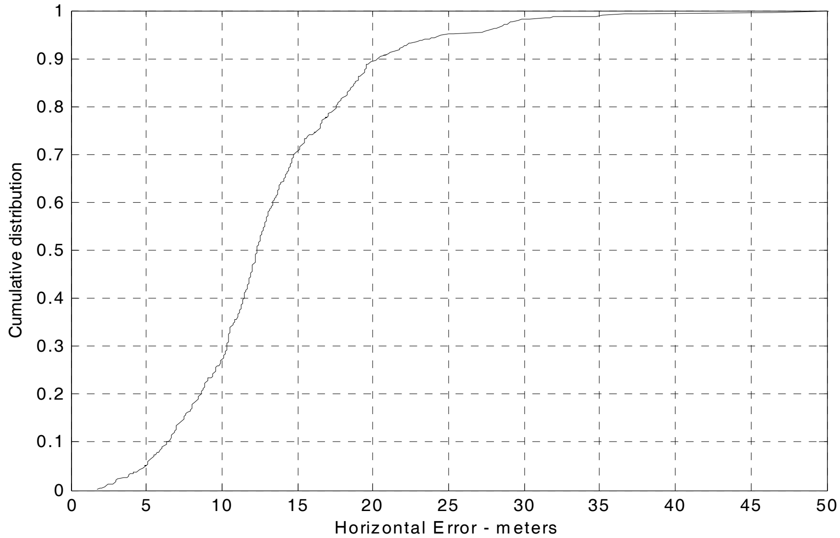
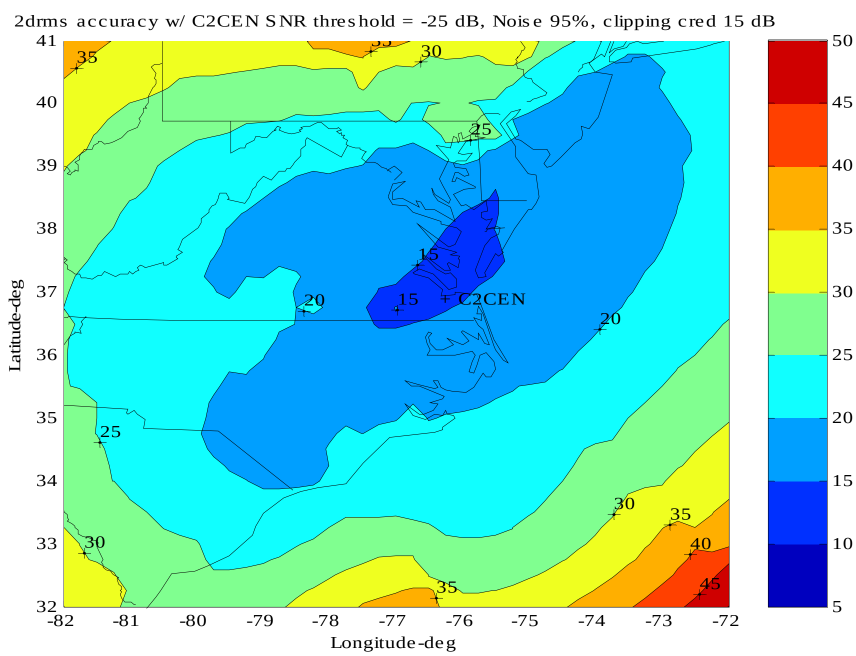


Figure 4.8-2. Expected Accuracy Contours (in Meters at the 95 Percent Noise Level) for a Sample Modernized Loran Design in the Chesapeake Bay Area



4.9 Maritime HEA Model Results

The initial tests performed by the evaluation team demonstrate that modernized Loran can be used as a back-up to GPS in the HEA. The sample output from the HEA model (refer to Figure 4.8-2) provides an indication of the output of the performance model. What follows are additional coverage plots and associated discussion to further demonstrate Loran's capability to meet the new HEA requirements. A discussion of the parameters used in the model is contained in Appendix C.

4.9.1 HEA Coverage

Because accuracy requirements vary from port to port, the HEA results are presented in two different ways. Figure 4.9-1 shows the various availability contours for 20-meter accuracy.

Figure 4.9-1. Expected HEA 20-Meter Accuracy Modernized Loran Coverage (Availability Contours in Percent at a Station Availability of 0.999) in the Conterminous United States with the Existing Infrastructure

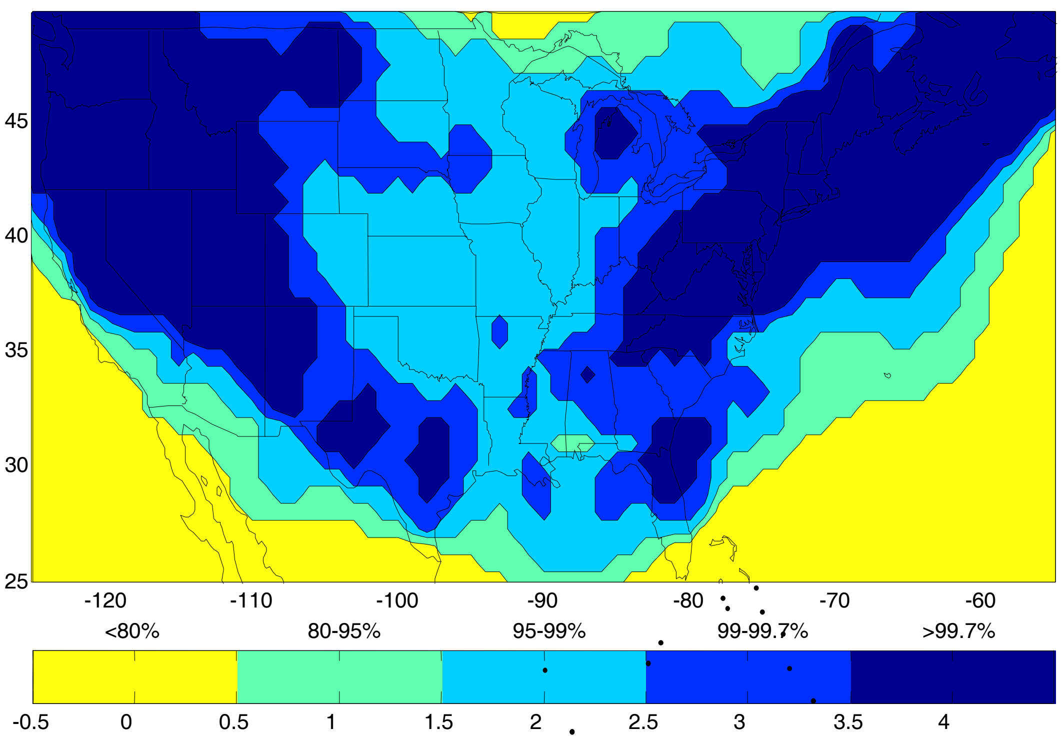
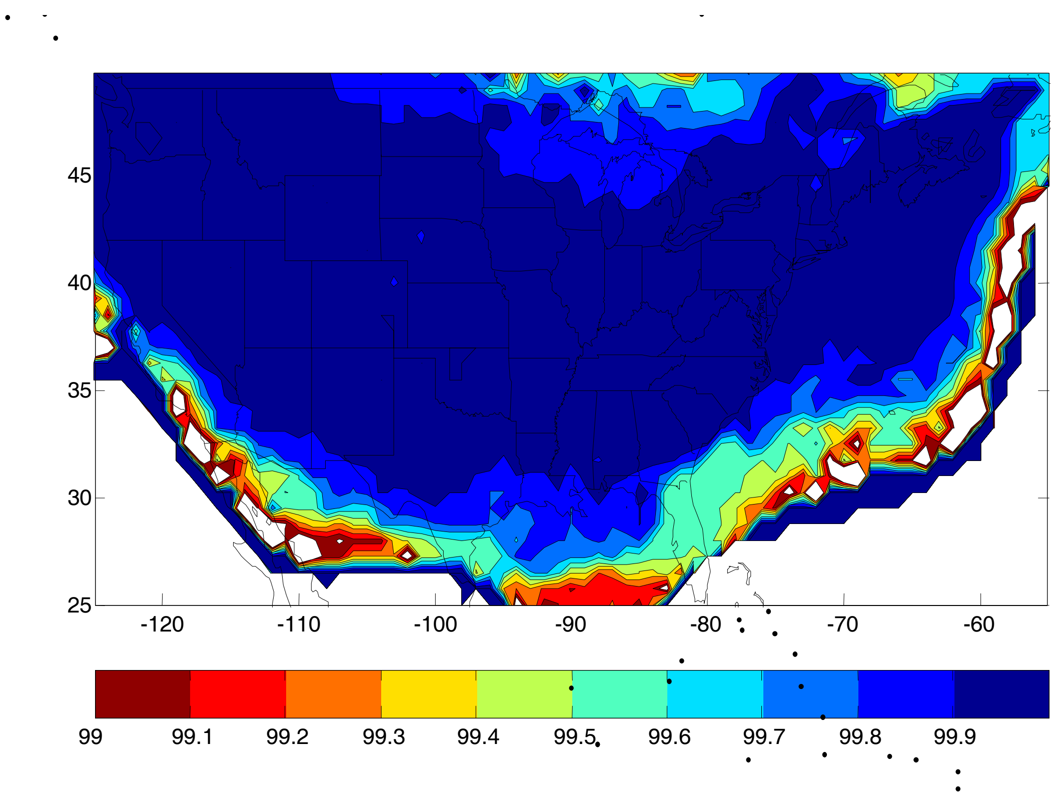


Figure 4.9-2 shows the associated continuity levels. As was the case in the aviation application, comparisons show that at any given location, the continuity levels always exceed the availability levels.

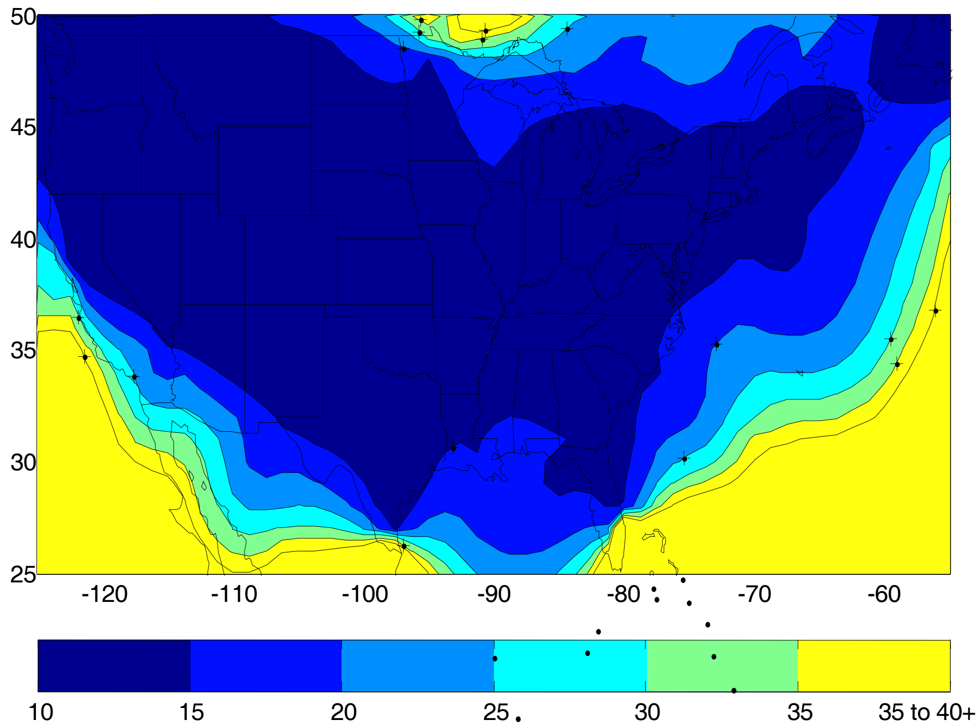
Figure 4.9-2. Expected HEA 20-Meter Modernized Loran Coverage (Continuity Contours in Percent for Station Continuity of 0.99) in the Conterminous United States with the Existing Infrastructure



The second way of examining the coverage is to fix the noise level and see the resulting 2-drms accuracy contours. Traditionally[72] the Coast Guard coverage diagrams are plotted at the 95 percent noise level. Accuracy contours at that level are shown in Figure 4.9-3.

[72] E.g., as is done in References 17 and 18.

Figure 4.9-3 Expected HEA Modernized Loran Coverage (Accuracy in Contours in Meters at the 95 Percent Noise Level) in the Conterminous United States with the Existing Infrastructure[73]



These results show that when differential corrections are used, the Loran-C system can meet the 20-meter requirement at 44 of 53 conterminous U.S. critical port areas. For the nine ports that fall short of the 20-meter goal, that level of accuracy could be obtained, if warranted, by installing two Loran stations in the Gulf of Mexico region and one in Southern California.[74] Alternatively, the 20-meter accuracy might not be required in all nine of those ports. As Table 4.9-1 shows, if 35-meter accuracy would suffice for HEA, only two of the ports would fall short, even with the current number of transmitting stations.

In Section 3.2.2, the concept of using the target level of safety (TLS) technique to establish marine requirements was briefly introduced. In this method, the probability of a marine incident (grounding) is computed as a function of the physical parameters of the waterway and the class of vessel. The requirements for the navigation aids/systems used by the waterway/vessel are established so that the TLS (based on vessel incident

[73] Infrastructure includes the Canadians stations.
[74] These new stations would also improve the coverage for aviation.

historical data) is met. The TLS can be adjusted up or down from the historical value based on the safety policy of the appropriate maritime authority.

Table 4.9-1. Major Ports Where Modernized Loran Is Currently Being Considered

	Ports with Predicted Coverage of:			
	20 m or less	21 m–3 m	> 35 m	> 50 m
Current Loran-C Stations	44	7	2	0
With Additional Southeast Coast Loran-C Stations	49	4	0	0
New West Coast Loran-C Station	48	3	2	0
New Southeast and West Coast Loran-C Stations	53	0	0	0

4.9.2 Acceptance in the HEA Applications

A critical issue regarding use of modernized Loran in the HEA environment is the user's operational need for an independent HEA capability. As in the aviation applications, this is an individual user decision based on the user's tolerance level for operational effects of GPS outages. Once again, user acceptance also requires a government commitment to provide the service for a viable commercial market to be generated. The modernized Loran receiver could be implemented as a stand-alone device or as part of a combination GPS/modernized Loran system. The combination receiver has the benefit of being able to support current Automatic Identification System (AIS) transponders. In a GPS outage environment, the positioning source would change from GPS to modernized Loran and allow for continued position reporting in the critical port environment. Other factors for acceptance include—

- Establishment of a network of differential Loran monitor sites
- Finalization of the modernized Loran data channel modulation method
- Development of RTCM specifications for maritime equipment.

4.10 Timing and Frequency Performance Analysis

The precise time and frequency users of Loran are important and are likely to be the largest modernized Loran user group and benefit most from the changes being made. Building on the LORIPP and LORAPP analyses and in keeping with the original tasking, the evaluation team examined if and how the precise time and frequency user groups were affected by the identified modifications to Loran-C. The timing community is divided into timing users and frequency users. As shown in Section 3, each group has its own set of metrics and measurement techniques. Frequency users greatly outnumber timing users and are concerned only about the rate of change of a clock—the actual phase difference is of no concern. Timing users are concerned about the phase offset between two clocks or between a clock and UTC—maintaining a constant phase offset infers a frequency requirement. Also, most timing users do not require a high level of synchronization. This section addresses the analysis of Loran-C's performance as it pertains to time and frequency applications.

4.10.1 Time and Frequency Considerations and Concerns

GPS provides a global method of recovering UTC. Time recovery performance with GPS ranges from 5 to 100 nsec depending on the method used. Because of its worldwide availability, ease of use, and low cost for timing and frequency applications, GPS is used for all timing requirements from 10 nsec to 1 second. The development of GPS as a commodity product has created a large market for its use, even when its performance exceeds requirements by many orders of magnitude. The scale of the timing and frequency market creates a dependence on GPS that, if exploited, can create financial, logistical, and security issues in the United States. If modernized Loran can serve as an alternative for timing and frequency users, the GPS dependence issue is significantly reduced.

As a viable alternative to GPS for timing and frequency applications, Loran-C time synchronization requires an order of magnitude improvement. Studies were conducted on legacy Loran-C data to determine the performance level and significant factors that limit performance [42]. On the basis of data collected from the National Institute of Standards and Technology (NIST) and USNO, legacy Loran-C time recovery provides synchronization to UTC at the 1-μsec level and frequency synchronization of 1×10^{-12} (with 24-hour averaging). From analyzing the legacy data, the following conclusions were drawn:

- The drift of the clocks at the Loran-C station and the seasonal change in propagation delay between Loran-C transmitters and users limit timing accuracy. These issues can be addressed by using differential corrections that provide for cancellation of common-mode noise (e.g., clock drift and correlated changes in propagation delay). Analysis of the legacy data resulted in a predicted order of magnitude improvement for modernized Loran, with time recovery within 100 ns of UTC.
- Frequency recovery with Loran-C already satisfies most users, if they can average for long periods of time (only 24-hour data were available for analysis). Frequency recovery performance would be improved with modernized Loran if the discontinuities in the transmitted signals were eliminated. The discontinuities are difficult for phase-locked loops to track and create a large design burden on the receiver manufacturers. Lower noise transmission would also result in shorter averaging times to achieve the same frequency stability.

4.10.2 Timing and Frequency Analysis and Tests

A study was organized to determine how timing and frequency users would benefit from a modernized Loran with the following features:

- Modernized Loran will include the transmission of differential corrections that will be used to reduce the common-mode timing noise between the transmitter and the timing user. These corrections will be derived from a network of time-based monitors.

- Clocks at the modernized Loran transmitters will be steered to within 20 nsec (rms) of UTC at all times.
- Time adjustments (of the transmitted signal) will be introduced using small changes of frequency rather than stepping the phase of the transmitted Loran signal.
- Calibration techniques will be developed to enable repeatable recovery of UTC (USNO) below 100 nsec (rms).

4.11 Timing and Frequency

To establish the expected performance of modernized Loran for timing and frequency users, a test network was installed with three timing nodes. The sites included NIST and Timing Solutions, Inc., in Boulder, Colorado, as well as Loran Station (LORSTA) in Gillette, Montana,. Data were collected over 3 three months to gauge expected performance.

4.11.1 Timing and Frequency Results

Table 4.11-1 summarizes the data collection results:

Table 4.11-1. Timing and Frequency Performance

Performance Category	Results	Comments
Time Recovery	10-40 nsec (rms)	Differential system where corrections applied over a 300-mile baseline
Frequency Recovery	1×10^{-11} with 1-hour averaging 1×10^{-12} with 3-hour averaging 1×10^{-13} with 3-day averaging	Performance to improve when discontinuities are removed (part of modernized Loran)

The time recovery performance of the modernized Loran network (using differential corrections) is well below the 100 nsec goal using a 300-mile network in the midsection of the United States. Additional nodes will be installed on the east coast to determine if the performance will degrade for more challenging propagation scenarios. It is clear from the research and experimental results that the differential service provided by modernized Loran significantly reduces the common-mode noise, which allows time recovery below 100 nsec and establishes modernized Loran as a viable alternative to GPS for precision time recovery in the United States [43].

Frequency recovery performance already meets the critical Stratum I specification that is required by the telecommunications industry. Frequency recovery will improve because the phase discontinuities in the modernized Loran era will be removed, and the differential corrections will enable very long averaging times (2 to 4 months).

4.11.2 Acceptance in the Timing and Frequency Community

A major issue regarding usage by the timing and frequency community is that, despite some users, the community is generally unfamiliar with the Loran-C system and its capabilities. As with aviation and maritime users, decisions to embrace modernized Loran will also be affected by the tolerance any given user can have for GPS outages. Other factors for acceptance include—

- The current Loran-C concept of operations (CONOPS) for entering timing adjustments must be changed from discrete steps to gradual adjustments.
- The current Loran-C SAM method must be changed to TOT.
- A monitor system is needed that has the highly accurate time base required for timing corrections. The current Loran-C transmitter stations can serve in this role.

4.12 LAND USER APPLICATIONS

Although new or revised requirements have not been identified for Loran-C land uses, numerous land applications used Loran-C before the general availability of GPS (e.g., vehicle, asset, animal, or human monitoring or tracking applications [33], [34]). The use of modernized Loran is still viable for these applications, especially for critical or high economic value application where there would be a safety or economic benefit gained by having a system available in the event of a GPS outage or where GPS satellites may not be visible (e.g., for tracking hazardous cargo). However, before these applications and Loran-C use can be evaluated, the specific requirements should be identified and validated. The evaluation team's methodology as described in this report is directly applicable to land-use applications.

4.13 EFFECT OF NON-AVAILABILITY OF CANADIAN STATIONS OR ADDITION OF NEW STATIONS ON COVERAGE

An assumption that the original infrastructure will continue to include Canadian stations may not be entirely valid. The desired modernized Loran coverage (e.g., where RNP or HEA requirements are met) would be reduced if this assumption were invalid. Also, should additional coverage be desired, one possible option would be to establish additional Loran station(s). The following two subsections examine these two situations. It is important to emphasize that neither the LORIPP nor the LORAPP is advocating any option—this is outside the scope of this technical evaluation. *The appropriate government agencies will have to make decisions that exercise various government-controlled options*. These decisions should consider the costs associated with coverage changes and consider all available options, their benefits and costs, and agreement among agencies on the best option. The only purpose of this discussion is to demonstrate the versatility of the modernized Loran model and the model's ability to illustrate how the loss or addition of a station affects coverage.[75]

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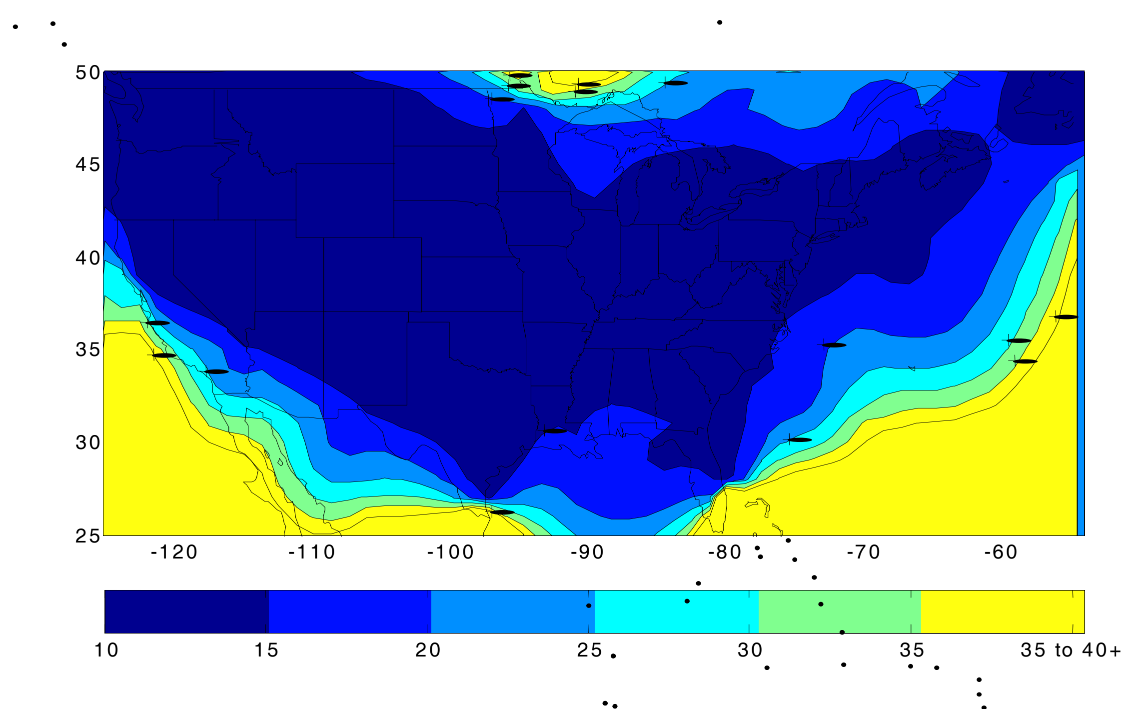
75 These sections presuppose that the addition of new stations or that the retention of Canadian stations are the only available trade space alternatives when analyzing coverage needs. Other trade space alternatives or changes in the

4.13.1 Effect of Non-availability of Canadian Stations on Coverage

An assumption made in Section 4.2.1 that must be reviewed is that the original infrastructure will continue to include the Canadian stations. If this assumption is not valid, the coverage will be reduced by the loss of the Canadian stations. More important to this discussion is whether the loss in coverage would be acceptable to government agencies. If this is not the case, the loss of coverage requires an analysis to determine how best (e.g., best benefit/cost ratio based on all options) to satisfy the specific requirements in these areas. In this case, the bound is the costs of the existing stations because it is unlikely that new stations would be established to replace the existing coverage and stations.[76] The reduction in coverage because of the non-availability of Canadian stations is illustrated in Figure 4.13-1 and Figure 4.13-2.[77]

Figure 4.13-1. Expected HEA Modernized Loran Coverage (Accuracy Contours in Meters at the 95 Percent Noise Level) in the Conterminous United States with the Canadian Stations

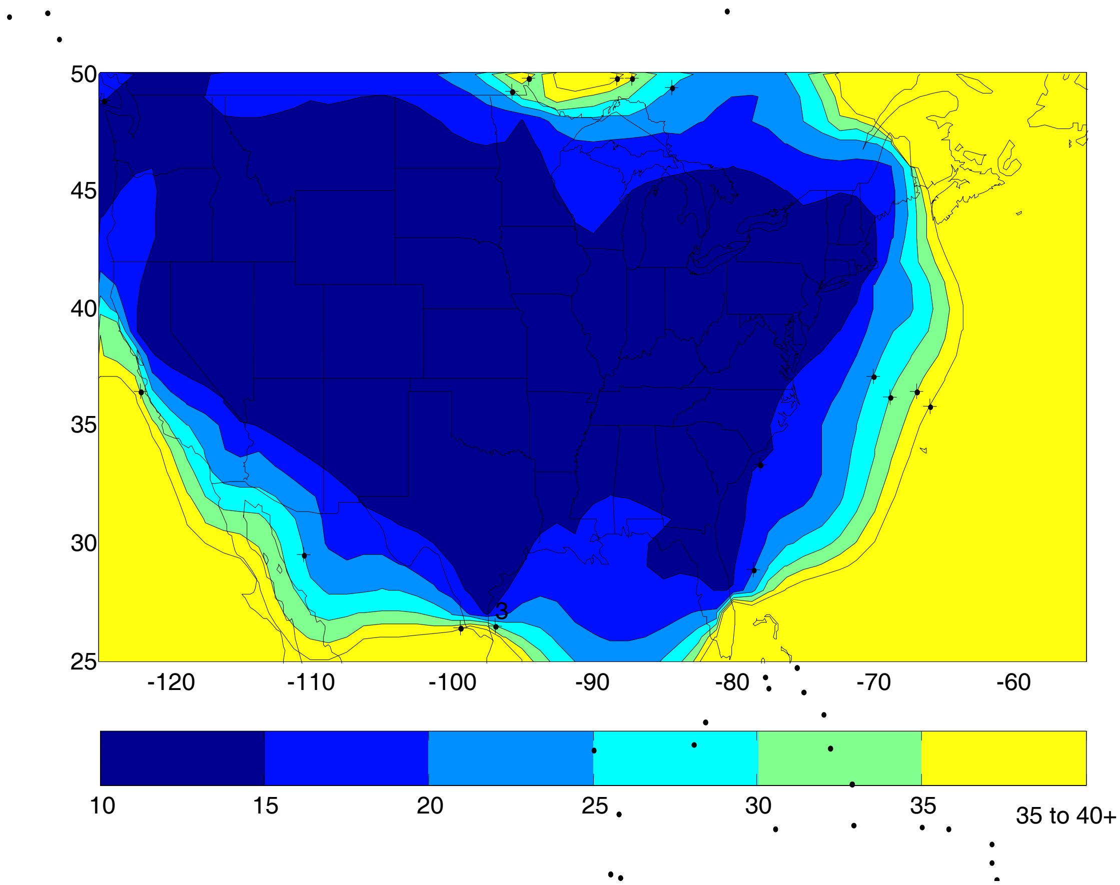


requirements (e.g., as discussed at the end of Section 4.9.1, HEA Coverage) in a specific area may be available, and other alternatives may exist to achieve desirable economic or other national security advantages using Loran-C.

[76] These available options are government functions related to carriage requirements and usability of equipment in given areas and circumstances.

[77] The aforementioned Volpe benefit/cost ratio would have to be recomputed based on the changes to the infrastructure and resulting changes in coverage.

Figure 4.13-2. Expected HEA Modernized Loran Coverage (Accuracy Contours in Meters at the 95 Percent Noise Level) in the Conterminous United States without Canadian Stations

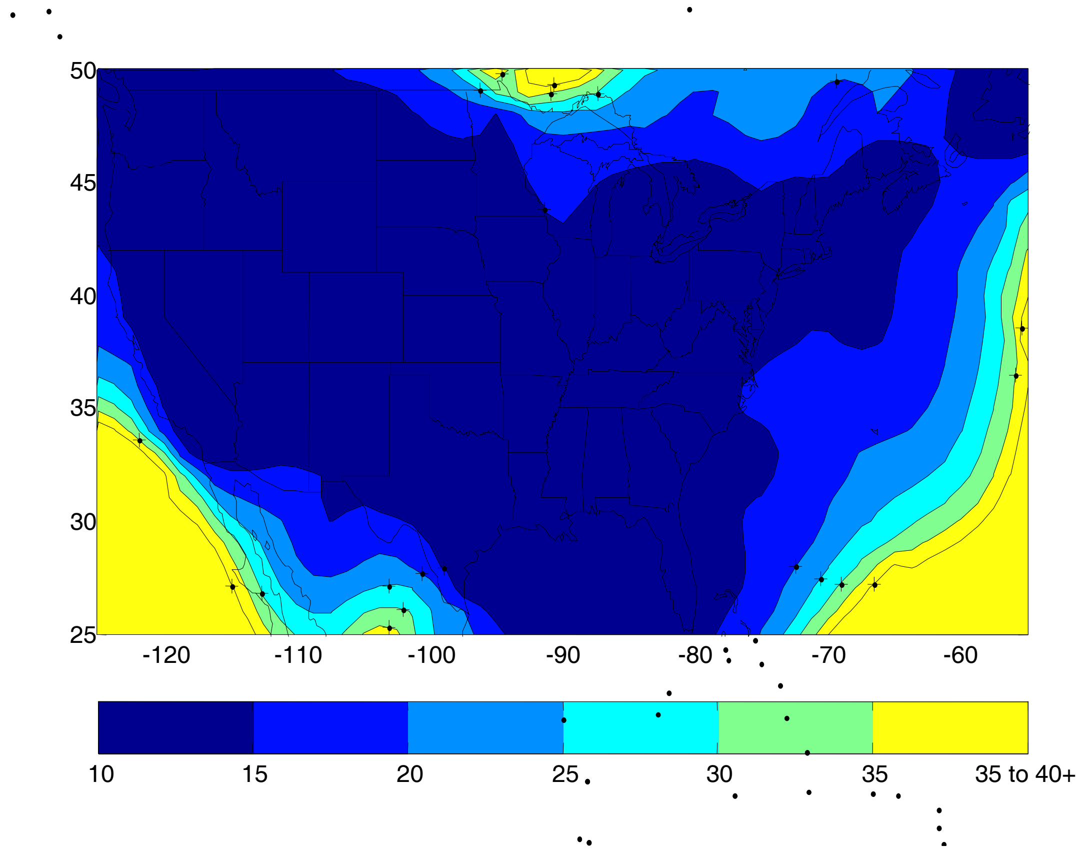


4.13.2 Effect of Adding New Stations on Coverage

The current Loran-C infrastructure may not satisfy the desired requirements at every CONUS port, airport, or other coverage area. An analysis is required to determine the best means (e.g., best benefit/cost ratio based on all options) to satisfy the specific requirements in these areas. To assist in this decision process and to bound the costs, the following approach is proposed. The upper bound for additional costs in the case of additional coverage is to add new stations (other options would be less costly). These new stations could provide adequate coverage for the areas where the existing infrastructure is not expected to provide the required level of service. The differences between existing infrastructure coverage and the expected coverage with additional stations are illustrated in Figure 4.13-3.[78]

[78] The new stations would add to the recurring and non-recurring (i.e., all costs including costs of additional surveys if necessary) portions of the cost equation but due to the original benefit/cost assumptions the benefits derived have not changed. Thus the benefit/cost ratio is reduced. But this does not mean that the addition of stations is an unreasonable option. This option, as well as other options, may be reasonable. The impact of each option would have to be reviewed in the context of the aforementioned Volpe benefit/cost assessment or follow-on assessment.

Figure 4.13-3. Expected HEA Modernized Loran Coverage (Accuracy Contours in Meters at the 95 Percent Noise Level) in the Conterminous United States with the Canadian Stations and New Stations in San Clemente, Guantamano Bay, and Yucatan



5. LORAN MODULATION

Several methods of superimposing communications on the Loran-C navigation signal have been explored over the years. Historically, Loran-C communications channels have been able to support very low-speed data communications (typically 10 bits per second [bps] or less). More recently, the European Loran-C community has developed the Eurofix system, which has increased the data throughput to approximately 35 bps [23].

European success sparked the idea of using Loran-C to communicate the WAAS messages at 250 information bps. The reasoning was that the Loran data channel (LDC) would be able to provide WAAS corrections to regions where the WAAS geostationary satellites exhibit periodic or complete interruptions in signal availability (e.g., in Alaska, where there is high terrain and the satellite is at a low elevation, or in natural or urban canyon regions). An early goal of the project was to determine whether a communications method could be devised that would meet the data rate provided by the WAAS system. This was accomplished, and the capability of LDC to successfully send WAAS messages was demonstrated during various flight trials. Further discussion on the WAAS-related LDC efforts is found in References [85] and [86]

In March 2002, the project shifted its goal from a WAAS communications capability to demonstrating Loran-C's ability to meet the new navigation and timing and frequency requirements found in Section 3.2.[79] One necessary capability to meet these requirements was for Loran-C to transmit vital information on the Loran-C system status directly to the user's equipment. These applications do not require the WAAS data rates, so a different, less complex, modulation method was developed. The current state of the modulation method is discussed in the following subsections.

5.1 DATA REQUIREMENTS

The LORIPP's iterative process identified a need to provide an aviation integrity warning. The LORAPP then identified a need to provide Loran differential corrections to meet the HEA accuracy requirements. Finally, timing requirements were identified to achieve precise time recovery (e.g., a time stamp). The evaluation team determined that developing a single communication modulation method—9th pulse communication—could satisfy these requirements. This modulation method has minimal impact on legacy users, does not interfere with Eurofix, and does not change Loran's allocated frequency spectrum.

5.2 PROPOSED MODULATION METHOD (9^{TH} PULSE MODULATIONS)

Selecting the modulation method was an iterative process that considered different alternatives and modulation methods [87]. The method selected by the evaluation team that satisfied all concerns and performance requirements added a 9^{th} pulse to the navigation group of eight pulses. This modulation has the following characteristics:

- Pulse position modulation (PPM)

[79] During the March 2002 FAA Murder board, the technical issue and focus became NPA.

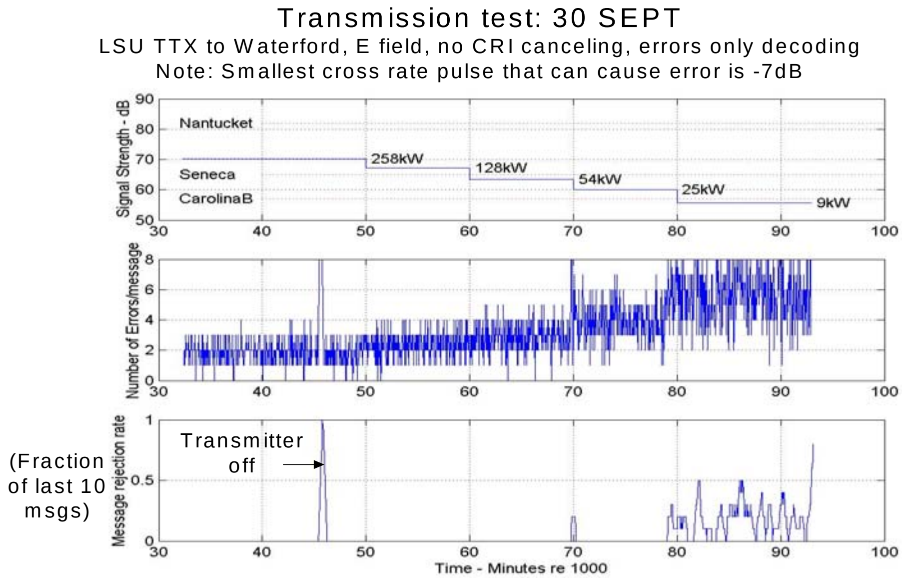
- Modulated pulse that is additional or 9th pulse, 1,000 μsecs after the last navigation pulse in the group
- Thirty-two state positions resulting from 5 bits/GRI (3 bits phase, 2 bits envelope and phase)
- Reed-Solomon forward error correction algorithm
- Message integrity greater than 10^{-7}
- Message length of 24 GRIs or a maximum of 2.38 seconds
- Messages limited to 45 information bits
- Do not have to demodulate more than the strongest signal to get absolute time, positively identify all signals, and get all corrections for an area
- Blanked 9th pulse in cross rate; other 8 could be cancelled
- Time to alarm: 24 GRI format, max 2.38 sec message length
- Message types with different priorities in the queuing process
- Time to first fix 2 to 4 minutes based on—
  - TOT control
  - Three messages/site @ 2 corrections/message
  - Assume maximum of 20 to 40 sites / LORSTA, 60 to 120 messages
  - Dual-rated stations.
- Averages to zero in legacy receivers, CRI increases to 0.5 dB
- PPM means no transmitter modifications, modulation done in software in time and frequency equipment.

5.3 RESULTS OF THE 9TH PULSE MODULATION TESTS

As described in Section 5.2, the 9th pulse communication method has been designed, developed, and tested. Test monitor sites were installed and communications with a test transmitter were established. The monitor successfully sent data to the transmitting site for transmission and receipt by the user equipment. The user equipment demodulated the information and the correction was applied to the Loran signal to produce the desired results.

Figure 5.3-1 exemplifies and supports the effectiveness and capability of the 9th Pulse communication system. The figure shows that during on-air testing no messages were lost until the modulated signal's relative power fell below the three strongest non-modulated stations.

Figure 5.3-1. Data Modulation Test Performance



The Reed-Solomon forward error correction algorithm is a good match for the bursty-type nature of the channel. The integrity of received messages can be satisfied through the Reed-Solomon code [87].

A prototype version of the modulator using the TTX was available for the test bed (Section 4.8.4 and Reference [49], [87]). In addition, two versions of prototype user equipment were built and used in the test bed. A prototype version of the modulator for the SSX has also been successfully tested.

The final prototype of the equipment began testing in late 2003. The results to date indicate that the 9^{th} pulse communication channel is sufficiently robust and error-free to meet the requirements of the LORIPP, the LORAPP, and the precise time users.

6. CONCLUSIONS OF THE EVALUATION TEAM

The results of the technical evaluation show that the modernized Loran system can satisfy the current NPA, HEA, and timing/frequency requirements in the conterminous United States. This conclusion is based on the following actions: a rigorous analysis of the application's performance requirements; expected modification of radionavigation policies, operating procedures, transmitter, monitor and control processes and user equipment specifications; completion of the identified Loran-C infrastructure changes; and results of numerous field tests. The assumptions listed in Section 4.2 are considered valid. The validity of these assumptions is based on the completion of the modernization project, promulgation of new radionavigation policy, changes in operational doctrine, and revised specifications for receivers and sensors. When this work is completed, the modernized Loran system will meet the current multi-modal user requirements. Collectively, the work completed creates the architecture for the modernized Loran system, which can be described as follows:

> The modernized Loran system continues to be a low-frequency, terrestrial navigation system operating in the 90- to 110-kHz frequency band and synchronized to UTC. However, this modernized Loran system has a recapitalized infrastructure and a new communication modulation method that enables operations that satisfy the accuracy, availability, integrity, and continuity performance requirements for non-precision approaches and harbor entrance and approaches, as well as the requirements of non-navigation time and frequency applications. Required changes to the current system include modern solid-state transmitters, a new time and frequency equipment suite, modified monitor and control equipment, and revised operational procedures that new receiver technology can exploit.

Modernized Loran's impact on legacy users is minimal; however, legacy users will not be able to take advantage of all system improvements. Also, due to the availability of receivers that can take advantage of the modernized Loran system, its benefit would likely be seen in some applications (e.g., timing and frequency) before others (e.g., aviation).[80] Regardless, *the evaluation shows that the modernized Loran system can satisfy the current NPA, HEA, and timing/frequency requirements in the conterminous United States and could be used to mitigate the operational effects of a disruption in GPS services.*

This report describes modifications to the existing Loran-C system that could make Loran capable of meeting NPA for aviation, HEA for maritime, and time/frequency user needs. If the decision is made to retain Loran as one of the federally provided radionavigation systems, the extent to which these modifications are accepted and implemented will define the actual characteristics of the resulting enhanced Loran (eLoran) system, *thereby allowing the users to retain the benefits they derive from their use of GPS.*

[80] Discussion of the actual benefits that can be derived is left to the Volpe benefit/cost assessment report.

7. RECOMMENDATIONS FOR FOLLOW-ON ACTIONS

If the decision is made to modernize and continue Loran as a federally provided radionavigation system, the evaluation team recommends actions be taken by both government and private entities to ensure that the system can reach and sustain its full potential as quickly as possible and into the foreseeable future. These recommendations would—

- Determine the actual coverage where the operational requirements are satisfied. (e.g., high atmospheric noise and Alaska).
- Expedite when the system would be able to be used.
- Provide the capability for additional applications.
- Ensure a diverse and competitive supply of multi-functional user equipment in the near term and throughout the life of the system.
- Promote the further understanding, development, and adoption of the system.

7.1 RECOMMENDATIONS FOR FOLLOW-ON ACTIONS (GENERAL)

The recommendations of the evaluation team are presented below in terms relative to the trade spaces (Section 2.4) and the major position, navigation, and time applications (Section 3.2). The following potential next steps apply to all applications.

7.1.1 Recommendations for Follow-on Actions (Radionavigation Policy)

In addition to the work required to ensure that the assumptions identified in Section 4.2.1 are valid, recommendations for potential radionavigation policy are as follows:

- Definitively announce the Federal Government's policy to continue, in the long term, the modernized Loran system as part of the critical national infrastructure for position, navigation, and timing/frequency applications.[81] This will encourage the development and use of the new Loran technologies (e.g., improved receivers, antennas, algorithms, etc.).
- Identify additional critical applications in which safety, security, and economic requirements must be met in the event of a GPS outage, and support Loran's use in these applications where applicable.
- Periodically update the benefit/cost assessment and expand its scope (e.g., develop business cases) to include all redundant, back-up, and contingency systems and all mechanisms for benefit for various applications.

[81] The evaluation team realizes that "long-term" is vague. The team also realizes that if the decision is made to modernize and continue Loran that technical aspects of the conclusion will not be valid without industry and user acceptance. This can only be gained if they are assured that there is sufficient time for benefits to be accrued from the use of modernized Loran. The actual date is beyond the scope of this evaluation and would be predicated on many factors including information provided in the Volpe benefit/cost assessment, user acceptance, GPS and Loran strategic plans.

- Revise agency and international agreements involving modernized Loran.
- Establish a common lexicon and metrics for describing and evaluating navigation systems with validated requirements (e.g., integrity, availability) for the applications.
- Conduct research and development evaluations to further examine potential Loran applications or to allow the use of modernized Loran in existing applications.

7.1.2 Recommendations for Follow-on Actions (Operational Doctrine)

In addition to the work required to ensure that the assumptions identified in Section 4.2.2 are valid, recommendations for potential operational doctrine work are as follows:

- Periodically review and, if necessary, update the signal specification and operations doctrine (e.g., electronic format on NAVCEN site).
- Provide operational performance data to the public.

7.1.3 Recommendations for Follow-on Actions (Transmitter, Monitor, and Control Equipment)

In addition to the work required to ensure that the assumptions identified in Section 4.2.3 are valid, recommendations for potential transmitter, monitor, and control work are as follows:

- Federal Government development of strategic maintenance and modernization plans for Loran
- Federal research and development to further examine Loran applications to maximize potential benefits; for example—
  - Further investigate noise and propagation effects to allow for more precise estimates, which will lead to an improved model.
  - Examine modern receiver designs that effectively attenuate lightning noise, and the associated processing gain at high noise levels.
- Develop the methodology for early skywave detection
- Develop operational 9th pulse communications.

7.1.4 Recommendations for Follow-on Actions (User Equipment)

In addition to the work required to ensure the assumptions identified in Section 4.2.4 are valid, recommendations for potential user equipment are as follows:

- Continuously improve the calibration data collection techniques and maps for position, navigation, and timing (PNT) users.

- Provide federal support for the development of user equipment specifications and certification standards (e.g., RTCA, Inc.; RTCM; PTTI) [88].

7.2 Recommendations for Follow-on Actions (Application-Specific)

The following subsections address application-specific recommendations. These recommendations will also aid in meeting the assumptions identified in Section 4.2.

7.2.1 Recommendations for Follow-on Actions (Aviation-Related)

Potential next steps for aviation applications are as follows:

- Develop policies, processes, and procedures to use modernized Loran for NPA and in the NAS. [82]
- Identify aviation benefits from additional Loran stations.
- Establish a standard process to collect modernized Loran data (e.g., ASF, ECD) for NPA—possible revisions to Reference [89].
- Periodically revalidate the airport calibration data.

7.2.2 Recommendations for Follow-on Actions (Marine-Related)

Potential next steps for maritime applications are as follows:

- Determine the minimum number of monitors per harbor to meet HEA requirements.
- Establish a standard process to collect modernized Loran data (e.g., ASF, ECD) for harbor survey.
- Periodically revalidate harbor survey calibration data.
- Determine the applicability of modernized Loran to support maritime carriage requirements (e.g., ECDIS and AIS).
- Consider basing the development of performance requirements on other methods to analyze position, navigation and timing requirements (e.g., target level of safety).
- Identify additional waterways for applying modernized Loran and GPS or its augmentations.

7.2.3 Recommendations for Follow-on Actions (Timing/Frequency-Related)

Potential next steps for time and frequency applications are as follows:

[82] The marketplace ultimately decides if and where modernized Loran will be used. However, adding Loran to the approved navigation systems or as part of an approved applications or processes may enhance its usefulness and, thus, its value in the marketplace (e.g., VNAV with a barometric altimeter; see Appendix C).

- Improve overall synchronization of modernized Loran system clocks to UTC.
- Investigate how the robustness and accuracy of the modernized Loran system clock can support critical national infrastructure applications.

7.2.4 Recommendations for Follow-on Actions (Other-Navigation-and-Positioning-Related)

Potential next steps for other navigation and positioning applications are as follows:

- Determine potential applications and their requirements (i.e., rail, highway, mass transit, E911, HAZMAT tracking), ensuring that descriptions use the same terms and metrics used in this report.
- Identify and validate requirements for these applications.
- Use the evaluation team's methodology to examine applicable land-use applications.

APPENDIX A—THE ORGANIZATIONS, ROLES, AND PARTICIPANTS [83]

Loran Evaluation Program Logo Collection

[83] The names provided are the people currently serving in these positions (as of March 2004).

Organization	Role in Evaluation	Key Participants
Federal Government:		
Federal Aviation Administration	Evaluation lead agency	
Navigation Services	Program Manager (PM)	Mr. Mitch Narins
AIR-130	PM support (certification)	Mr. Bruce DeCleene
		Mr. Kevin Bridges
Systems Architecture	FAA PM support (architecture)	Mr. David Olsen
William Hughes Technical Center	PM support (Test Director)	Mr. Bob Erikson
		Mr. Scott Scholenberger
U.S. Coast Guard	Loran-C operations & maintenance	
HQ	FAA PM support (USCG PM for Loran-C)	CAPT Dennis Holland
		LCDR John Merrill
		LCDR Dave Dixon
		LT Dave Fowler
		CDR Dean Bruckner
Loran Support Unit	FAA PM support (Recap Lead)	CDR John Macaluso
		LT Kevin Carroll
C2CEN	FAA PM support (LORAPP Lead)	CDR Gordon Weeks
Coast Guard Academy	FAA PM support (Tech)	CAPT Dick Hartnett
NAVCEN	FAA PM support (Ops Lead)	CAPT Curt Dubay
		Mr. Gene Schlechte
		LCDR Max Caruso
		LT Kirk Montgomery
John A. Volpe National Transportation Systems Center		
	Cost-benefit analysis	Dr. George Skaliotis
		Dr. Jonathan Lee
		Dr. Walter Gazda
Industry:		
Booz Allen Hamilton	FAAPM Support & Evaluation Coordinator	Mr. Ron Davis
		Mr. Robert Wenzel
		Mr. G. T. Gunther
Peterson Integrated Geopositioning, LLC		
	FAA PM, LSU support (LORIPP Lead)	Dr. Ben Peterson
		Mr. Ken Dykstra
JJMA	USCGA tech support	Mr. Greg Johnson
		Mr. Christian Oates
		Mr. George Sanders
		Mr. R. Shalaev
Northrop Grumman Information Technology		
	General support to Evaluation Team	Dr. Pete Morris
Northrop/Grumman Simulation Systems	FAATC support	Dr. Robert Lilley
		Dr. Robert Stoeckly
		Dr. Jamie Cruz
Locus, Inc.	FAA support	Dr. Linn Roth
		Mr. Paul Schick
Megapulse, Inc.	FAA/USCGA/LSU support	Dr. Paul Johannessen
		Mr. Eric Johannessen
		Mr. Andre Grebnev

WR Systems	LSU support	Mr. Charles Schue Mr. Charles Teaney Mr. John Hartzell
FreeFlight Systems	PM support	Mr. Steve Williams Dr. Jim Davis
Reelektronika	FAA support	Dr. Durk van Willigan Dr. Gerald Offermans Dr. Arthur Helwig Mr. Wouter Pelgrum
Rockwell Collins	PM support	Mr. Jim Doty Mr. Patrick Hwang Mr. D. A. Anderson
Academia:		
Stanford University	PM support (LORIPP Lead)	Dr. Per Enge Dr. Sherman Lo Dr. Todd Walter Mr. Lee Boyce
Ohio University	FAA, USCGA support	Dr. Dave Diggle Dr. Frank van Graas Mr. Jaimie Edwards Mr. Curt Cutright Mr. Brian Branham
University of Alaska	PM support	Mr. Leonard Kirk Mr. Steve Mattingly
University of Rhode Island	USCGA and PIG support	Dr. Peter Swaszek
University of Wales	FAA support	Dr. David Last Dr. Paul Williams

APPENDIX B—ACRONYMS

A&T/Anteon	Analysis & Technology, Inc./Anteon
ABS	Automatic Blink System
ADF	Automatic Direction Finding
AIS	Automatic Identification Sysem
AIV	All in View
APA	Automatic Phase Adjustment
ASF	Additional Secondary Factor
BCA	Benefit/Cost Assessment
BIPM	Bureau International des Poids et Mesures
bps	bits per second
CCIR	International Radio Consultative Committee
CCZ	Coastal Confluence Zone
CONUS	Conterminous United States
CTE	Cross Track Error
CWI	Continuous Wave Interference
DARPA	Defense Advanced Research Projects Agency
DDC	Digital Down Converter
DGPS	Differential GPS
DME	Distance Measuring Equipment
DoD	Department of Defense
DOT	Department of Transportation
DSP	Digital Signal Processing
ECD	Envelope-to-Cycle Difference
EGNOS	European Geostationary Navigation Overlay Service
EST	Eastern Standard Time
FAA	Federal Aviation Administration
FRP	Federal Radionavigation Plan
FTE	Flight Technical Error
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRI	Group Repetition Interval
GUI	Graphical User Interface
HEA	Harbor Entrance and Approch
HMI	Hazardous Misleading Information
HPL	Horizontal Protection Limit
ICAO	International Civil Aviation Organization
IFM	Intrapulse Frequency Modulation
IFR	Instrument Flight Rules
ILA	International Loran-C Association
IMO	International Maritime Organization
IOC	Initial Operating Capability
JJMA	John J. McMullen Associates

LDC	Loran-C Data Channel
LF	Low Frequency
LNAV	Lateral Navigation
LOGIC	Loran-C/GPS Integrated Communications
LOP	Line of Protection
Loran-C	LOng RAnge Navigation
LORAPP	Loran-C Accuracy Performance Panel
LORIPP	Loran-C Integrity Performance Panel
LPA	Local Phase Adjustment
LSU	(USCG) Loran Support Unit
MOPS	Minimum Operational Performance Standard
NAS	National Airspace System
NAVCEN	(USCG) Navigation Center
NIST	National Institute of Standards and Technology
NM	Nautical Mile
NPA	Non-Precision Approach
nsec	nanosecond
OOT	Out of Tolerance
OU	Ohio University
PA	Phase Adjustment
PNT	Position, Navigation, and Time
PPM	Pulse Position Modulation
p-static	Precipitation Static
RAIL	Remote Automated Integrated Loran-C
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RNAV	Radio Area Navigation
RNP	Required Navigation Performance
RTCA	Radio Technical Commission for Aeronautics
RTCM	(Standalone Acronym)
SAM	System Area Monitor
SARP	Standard and Recommended Practice
SBAS	Space-Based Augmentation System
SNR	Signal-to-Noise Ratio
SSX	Solid State (Loran-C) Transmitter
TCS	Transmitter Control Set
TD	Time Difference
TFE	Time and Frequency Equipment
TLS	Target Level of Safety
TOA	Time of Arrival
TOT	Time of Transmission
TSC	Timing Solution Corporation
TSO	Technical Standard Order

TTX	Tube Type Transmitter
TWSTT	Two-Way Satellite Time Transfer
UPS	Uninterruptible Power Supply
US	United States
USAF	U.S. Air Force
USC	U.S. Code
USCG	U.S. Coast Guard
USCGA	U.S. Coast Guard Academy
USNO	U.S. Naval Observatory
UTC	Coordinated Universal Time
VFR	Visual Flight Rules
Volpe	Volpe National Transportation Systems Center
WAAS	Wide Area Augmentation System
W_G	WAAS via Geostationary Satellite
WIPP	WAAS Integrity Performance Board
W_L	WAAS via Loran-C

APPENDIX C—TECHNICAL BRIEFS PROVIDED TO SUPPORT THE CONCLUSIONS OF THIS REPORT

Section A—Presentation on “The Results of the Loran-C Evaluation”
Section B—Presentation on “LORIPP Evaluation of Loran-C for Aviation”
Section C—Presentation on “Report on Loran for Harbor Entrance Approach and RNP 0.3”
Section D—Presentation by Ohio University on “Loran-C P-Static”
Section E—“FAATC Preliminary Test Report”
Section F—Working Paper on “LNAV/VNAV Approaches Using Loran”

APPENDIX C—SECTION A— THE RESULTS OF THE LORAN-C EVALUATION

Presentation: “The Results of the Loran-C Evaluation”

APPENDIX C—SECTION B—LORIPP EVALUATION OF LORAN-C FOR AVIATION

Presentation: “LORIPP Evaluation of Loran-C for Aviation”

APPENDIX C—SECTION C—REPORT ON LORAN FOR HARBOR ENTRANCE APPROACH AND RNP 0.3

Presentation: “Report on Loran for Harbor Entrance Approach and RNP 0.3”

APPENDIX C—SECTION D—LORAN-C P-STATIC BY OHIO UNIVERSITY

Presentation: “Loran-C P-static” by Ohio University

APPENDIX C—SECTION E—FAATC PRELIMINARY TEST REPORT

Highlights—Loran P-Static Project Ground Electrostatic Tests

March 8–12, 2004

Highlights of Activities

Monday, March 8

1. Technical team briefing
2. Briefing for all participants (aircraft engineering, aircraft inspection, safety)
3. Rest of day spent unpacking equipment and repairing damaged collector fixtures.

Tuesday, March 9

1. Set up high-voltage power supply and data collection equipment (for ground)
2. Tested ion flood and collector fixtures
3. Troubleshot data collection problem
4. Fabricated missing corona balls and attachment screws
5. Fabricated missing legs for fixtures
6. Repaired grounding rod hook
7. Briefed fire department
8. Instrumented static dischargers installed on aircraft
9. Fabricated backup safety discharge equipment.

Wednesday, March 10

1. Placed aircraft on acrylic sheets and jacked aircraft
2. Removed exit door from aircraft
3. Checked bonding on aircraft
4. Conducted nitrogen purge of fuel tanks with modified tanking venting
5. Installed electrostatic charging, data collection, and Loran simulator equipment.

Thursday, March 11

1. Conducted test high-voltage charge of the aircraft with no personnel on board

2. Conducted field mill calibration

3. Conducted test with standard ASA-3 dischargers installed but with three TCO instrumented dischargers

4. Removed standard ASA-3 dischargers from aircraft. Replaced TCO dischargers with rods and added more rods using alligator clips. This simulates a bare aircraft without dischargers but preserves the aircraft.

Friday, March 12

1. Conducted test with “bare” aircraft. This is worst case.

2. Conducted second test with “bare” aircraft since no ground digital data were collected on the first run.

3. Conducted test with dischargers located in “optimized” locations. Again used alligator clips to attach the discharger. Placed a foil tape was on trailing edges and grounded to make discharger placement easier.

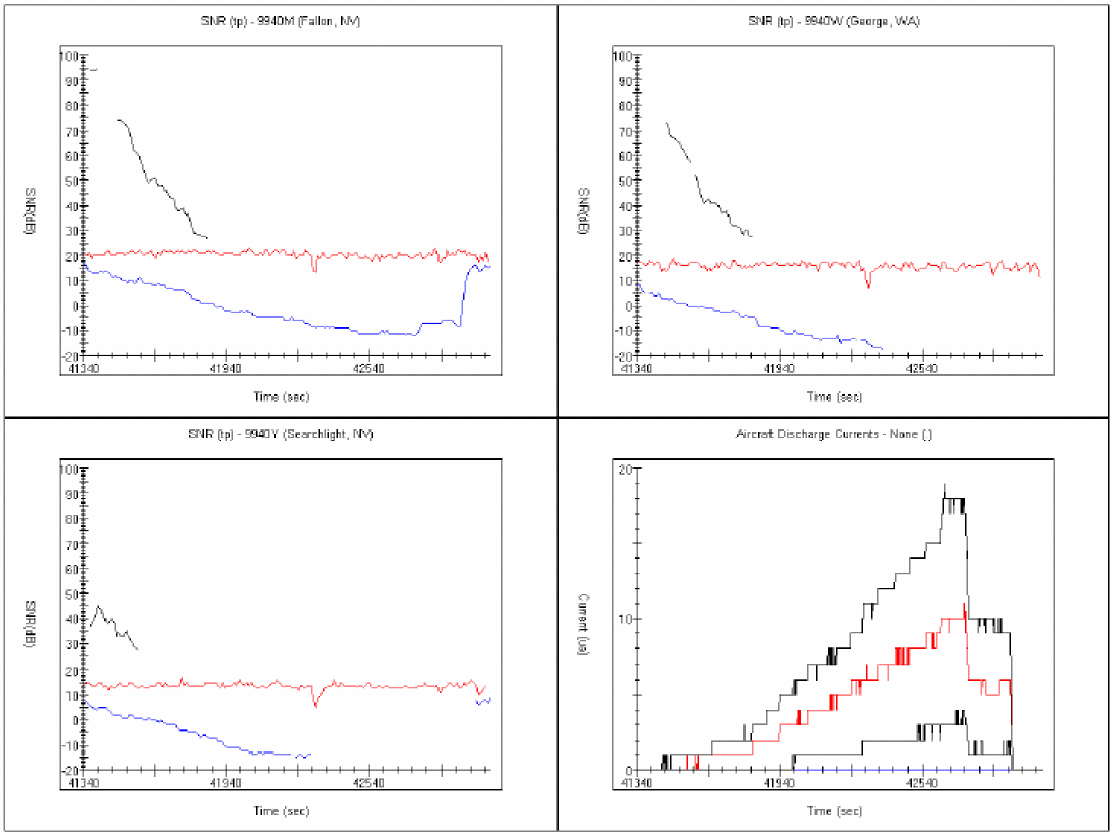
4. Conducted equipment tear down, packing, and cleanup of the area.

Test Results

Attached is a general photo of the test setup. The second attachment shows a plot of the received signal-to-noise ratios (SNR) for Fallon (M), George (W), and Searchlight (Y). Also included on the plot are discharger currents in microamps. The data are from the “bare” aircraft test. All SNR plots show the SatMate with H-field antenna in red, SatMate with E-field antenna in blue, and Apollo Multi-Chain Loran System (MCLS) in black. SNRs for SatMates are in dB, whereas the Apollo reports the SNR as counts in a range from 0 to 99. The Loran simulator was adjusted such that Fallon had no attenuation, whereas George was attenuated 6 dB and Searchlight was attenuated 9 dB. Signals were attenuated to ensure that the Loran receivers would be working with different field strengths and SNRs. Due to the use of a loop antenna, the received field strengths for an H-field and an E-field antenna may not be equal. It may be more appropriate to compare the E-field performance of Fallon with the H-field performance of Searchlight. Flight data using on-air Loran signals has been collected and will be used to adjust the signals if necessary. A quick review of the data shows that the SNR for the SatMate receiver with H-field antenna remained constant for each of the stations. E-field results for the SatMate showed the SNR starting at +17 and dropping to –12 dB at the end of the test. This is a drop of 29 dB. Results for George and Searchlight had similar slopes but stopping normal tracking before reaching the end of the test. The Apollo receiver showed a decreasing SNR value as the discharge current increased. When the Apollo reached a displayed SNR count of 30, it stopped normal tracking. For Fallon, the SNR count started at 75 and dropped to 30 before going out of normal track. This is only a 10 dB drop in SNR based on a calibration curve. This seems to indicate that the Apollo may not have the dynamic range or advanced signal processing capability of the SatMate receivers.

More analysis is required but these results seem to verify the results of previous tests conducted by others.

Robert Erikson
Test Director—Loran P-Static
March 15, 2004

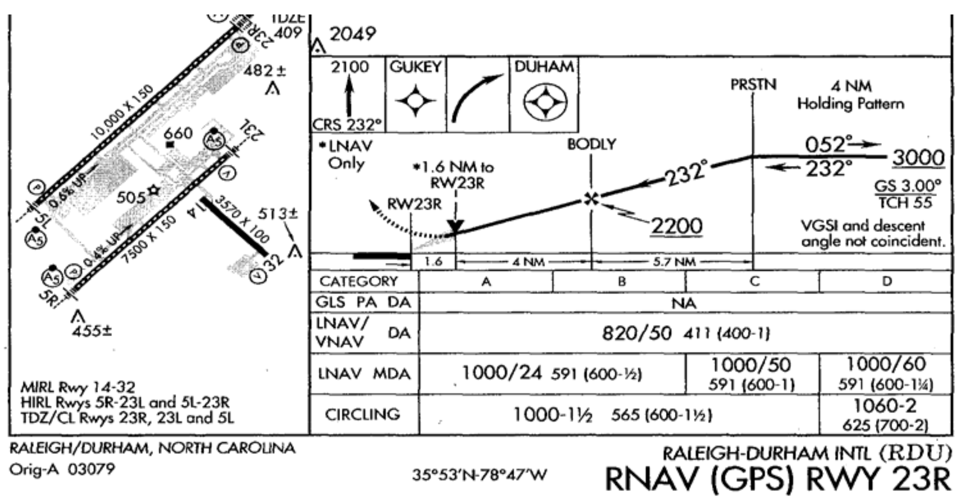


Legend: SatMate E-field = Blue, SatMate H-field = Red, Apollo = Black
Files: ACY3122004b_Evt.txt, ACY3122004b_SME.txt, ACY3122004b_SMH.txt, ACY3122004b_APL.txt, 3122004b.txt
Printed: 3/15/2004 12:49:32 PM FAA - W J Hughes Technical Center

APPENDIX C—SECTION F—WORKING PAPER ON LNAV/VNAV APPROACHES USING LORAN

A main focus of this evaluation is to provide the data and analysis to determine if Loran meets the accuracy, availability, continuity, and integrity requirements for RNP 0.3 navigation service in the National Airspace System. As such, Loran is typically only considered a Lateral Navigation (LNAV) system in a redundant navigation role. However, if Loran is an RNP 0.3 system, it can also enable Vertical Navigation (VNAV) for higher-end users through barometric altimeter aiding, a method currently in widespread use on aircraft equipped with flight management systems. Barometric aiding will permit properly equipped aircraft to take advantage of the lower minimums and safety benefits of vertical guidance associated with LNAV/VNAV approaches compared to LNAV-only approaches (see Figure C-F.1). The VNAV capability may make Loran attractive as a redundant navigation system to a wider aviation audience by increasing the dispatch and mission completion reliability for air carriers and high-end general aviation users.

Figure C-F1. Partial Approach Plate



New technology may also make Loran LNAV/VNAV available to smaller aircraft as well. Systems based on solid state micro-electromechanical systems (MEMS) and/or piezoelectric sensors and thermal probes that do not require traditional air data sensors/computers might make barometric-aiding available at a price affordable to those flying small piston engine aircraft. Having a redundant LNAV/VNAV capability to GPS WAAS might be desirable for small aircraft operators because they routinely fly to airports not served by ILS.

Advisory Circulars 20-129 and 90-97 provide an acceptable means, but not the only means, of obtaining airworthiness and operational approval to use barometric VNAV equipment.[84] But before these Advisory Circulars can be applied to Loran-based LNAV/VNAV approaches, the findings in this report must be used to create appropriate certification standards for RNP 0.3 Loran navigation equipment.

[84] Advisory Circular 90-97 currently lists only GPS and DME/DME navigation systems as eligible for barometric-aiding VNAV approval. Including Loran will require a minor update to the Advisory Circular.

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